Electromagnetic Theory approached via the guided TEM Wave

Electromagnetism 1

by Ivor Catt

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Quotes

Quotes

Then there were the remarkable researches of Faraday, the prince of experimentalists, on electrostatics and electrodynamics and the induction of currents ... The crowning achievement was reserved for the heaven-sent Maxwell, a man whose fame, great as it is now, has, comparatively speaking, yet to come.
- O. Heaviside, Electromagnetic Theory vol 1 pp 13/14, 1893.

Now, there are spots before the sun, and I see no good reason why the many faults in Maxwell's treatise should be ignored. It is most objectionable to stereotype the work of a great man, apparently merely because it was so great an advance, and because of the great respect thereby induced.
- ibid, p68.

Our electrical theory has grown like a ramshackle farmhouse which has been added to, and improved, by the additions of successive tenants to satisfy their momentary needs, and with little regard for the future. We regard it with affection. We have grown used to the leaks in the roof .... But our haphazard house cannot survive for ever, and it must ultimately be replaced by a successor whose beauty is of structure rather than of sentiment.
- H W Heckstall-Smith, Intermediate Electrical Theory, pub. Dent, 1932, p283.

It was once told as a good joke upon a mathematician that the poor man went mad and mistook his symbols for realities; as M for the moon and S for the sun.
- O. Heaviside, Electromagnetic Theory vol 1 p133, 1893.

... the universe appears to have been designed by a pure mathematician.
- Sir James Jeans, The Mysterious Universe, 1931, p115.

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[QUOTATIONS](#)

PREFACES

D S Walton

I studied Physics for my first degree at the University of Newcastle and stayed to complete a PhD before embarking on an academic career, being appointed to a Junior Lectureship in Trinity College, Dublin in 1971. In 1974, frustrated with academic life, I left to start a company whose aim was to exploit the rapidly expanding possibilities within digital electronics.

At the time the state of the art technology was represented by Schottky TTL, an evolved form of Transistor-Transistor logic using Schottky 'clamping' diodes in order to prevent device saturation and hence reduce propagation delay. A feature of this technology was that the logic signals had a transition time of 1.5 nS which was to lead to problems when systems were constructed from these devices.

As our fledgling company struggled to build a prototype of the logic analyser, which was to be our first product, I became increasingly frustrated by the difficulties we encountered in trying to build a reliable system. These problems resulted from phenomena like crosstalk and power supply transmitted noise, and I was puzzled by the apparent lack of any design guidelines or processes which would produce systems with predictable levels of reliability. It was clear that no progress would be made towards more reliable systems until we understood these phenomena and could lay down design rules for power supply design and distribution, and logic signal interconnections on printed circuit boards and backplanes.

It was as I was struggling with these issues that I met Ivor Catt during a sales visit I was making to Marconi Elliott Automation at Borehamwood. In the lift after the demonstration Ivor introduced himself to me and we seemed to cover a vast range of subjects from computer architecture to hardware design. Subsequently Ivor wrote to me enclosing information on his computer architecture papers and inviting me to stay with him on my next trip to the area.

Ivor Catt is one of the most original and creative thinkers I have ever had the privilege to know and there is no doubt that the progress we made together was largely dependent on his ability to bring a fresh perspective to familiar situations. I was particularly grateful for his explanation of the development of ECL (Emitter Coupled Logic) with which he was intimately involved as part of Motorola's team in the sixties. He also explained his view on TTL and S-TTL and their shortcomings.

I remember a telephone conversation about the transmission line nature of logic interconnections which established a basis for my future thinking and demonstrated the poverty of most of the contemporary writings on the subject.

At this time also Ivor sent me an unpublished manuscript of his book on logic design. I read this avidly and, I believe, surprised Ivor by finding an error in his technique for assessing the pulse performance of decoupling capacitors. Ivor's key point was that the so called 'stray inductance' attributed to capacitors was a myth. I particularly remember his comment that 'all of the stray inductance is not in series with all of the capacitance. In other words, from the point of view of a step pulse, the capacitor was distributed in space and therefore in time. It was as I reflected on this that I 'saw' that a capacitor was in fact a transmission line and the whole universe began to turn itself inside out with the transmission line becoming the fundamental primitive while other concepts such as inductance, capacitance, and mutual inductance were constructed from it.

I think Ivor's own words recorded at the time are the best history of what happened

next;

> *Then one night, [28 May 1976] as was his wont, Walton phoned Catt and talked about a number of things - how he knew he should get the sine wave out of his [conceptual] system but how difficult it was to do so; how he wondered how the particle came into Faraday's Law of Induction; that perhaps the Law was only an approximation and did not hold exactly at the atomic level. Catt wanted no particles introduced into the argument [!!].*
>
> *Then Walton raised the point about a 'Faraday's Law loop' with a capacitor as part of the loop. Catt said that if instead of a C you had the end of a very long 50 ohm transmission line it would look just like a resistor. ...... Walton said, "So that gets rid of displacement current". .... Catt and Walton promptly agreed that a capacitor was a transmission line.*

The work which Ivor, Malcolm Davidson, and I carried out over the next few years influenced not only the practicalities of designing digital systems but made a significant contribution to the development of electromagnetic theory. It is my sincere hope that a time will come when Ivor's contribution to electromagnetic theory will be accorded the position it deserves in the mainstream of the development of the subject.

Malcolm Davidson

In 1976, long before Personal Computers and microprocessors, when TTL was the de facto designer's building block, I was working on a military program for a large electronics company on the outskirts of London. I was still a fresh face engineer with merely 5 years of post graduate experience under my belt. Nevertheless, I was helping to design some digital test equipment utilising TTL. The system would ultimately interface to a DEC PDP 11. It seemed very interesting, but I was becoming increasingly perplexed that the paper design never seemed to work as planned and the staff appeared incapable of finding the problem. "Noise", "glitches", "race conditions", "spikes" and "flaky chips" were all popular choices to describe the poorly understood problems of the moment. This list soon had "bugs" added when software became part of the system. "Heaven help any military personnel who ever have to use this stuff," I thought.

"What was going on?", I wondered. "Why do all these problems appear to be insurmountable?" Someone suggested I go and talk to a contract engineer, some guy called Catt. He seemed to have a lot of ideas about the problems. So filled with a little hope and a lot of confusion, I set off to find this fellow, little knowing that those first few steps would be the start of a journey that has taken me far beyond circuit boards and logic chips. I found Ivor Catt, and listened intently as he spoke so eloquently and with such enthusiasm about issues that were at the time either half forgotten from college days, or entirely foreign to me.

TEM wave fronts, Oliver Heaviside, Transmission line theory, and Poynting Vectors. What had all this got to do with some paper logic design and a few TTL gates? I quickly found out that it had a tremendous amount to do with it, allowing me to resolve problems and tackle design issues that had hitherto seemed impossible. I decided to devote time to this apparent chasm between theoretical concepts and physical reality. I would feel pretty bad if some plane filled with 300 passengers crashed due to one of these so called "glitches".

With Ivor's good counsel and the help and support of David Walton, I began to uncover a treasure trove of knowledge. My first so-called discovery was in an engineering library at Marconi Elliott Avionics, where I found a book by J A Fleming from 1898. On page 80 he states;

> *It is important that the student should bear in mind that, although we are accustomed to speak of the current as flowing in the wire in one direction*

> *or the other, this is a mere form of words. What we call the current in the wire is, to a very large extent, a process going on in the space or material outside the wire.*

There it was, right in front of me in black and white! The current does not flow around a loop setting up a magnetic field as I had, along with countless other engineers, been taught in high school and university. It was the other way round. The electric current is but an artefact of a more fundamental entity. Over the next few years Ivor, David and I wrote numerous articles, gave a lecture series, and tried to have various papers published. I read voraciously, and began to realise that academia and industry based its beliefs, not on accuracy of knowledge, but on a "perceived accuracy", inextricably linked to the ego needs of worried individuals and their desire to retain the status quo.

Everyone has to justify a philosophical position taken by believing that it is the correct one, for to think otherwise would be sheer folly. To be convinced that some basic tenet of electrical engineering is wrong means a complete re-evaluation of the very theoretical structure that one has supported and believed in for many years. Scientific dogma has many fervent allies who continually resist change.

Regardless of challenges by us and especially by Ivor, attempts to cajole the engineering and academic world into rejecting some accepted theories and adopting a coherent set of somewhat different basic axioms have been fruitless. Many projects are still developed using inaccurate physical models, the saving grace being that designs have shrunk so rapidly in the last 10 years that the problems are less than they might have been. Designs that used to be in a rack now may reside on a card, and those once requiring a card now use an LSI chip. However, the problems will not go away, and difficulties still exist as engineers struggle to achieve reliable complex designs at clock rates above 20 MHz.

In the constant pursuit of improvement and quality, this book, outlining both scientific and political issues, is a must for every electronics company and every educational faculty. As a society, we need to spend more time reflecting upon our past and evaluating our progress. This book will stimulate discussion and debate, through which, hopefully, science can at last begin to place digital design on a foundation of solid, appropriate theories and concepts.

Those of you who feel that many of the ideas in this book are not mainstream should find a copy of "Standard Handbook for Electrical Engineers" by Donald G. Fink and H. Wayne Beaty. In all editions up to and including 12 (published in 1987), there is a section entitled "Electromagnetic Wave Propagation Phenomena". This seminal work gives a clear and unambiguous description of the role that conventional electric current plays in energy flow.

> *The usually accepted view that the conductor current produces the magnetic field surrounding it must be displaced by the more appropriate one that the electromagnetic field surrounding the conductor produces, through a small drain on the energy supply, the current in the conductor. Although the value of the latter may be used in computing the transmitted energy, one should clearly recognize that physically this current produces only a loss and in no way has a direct part in the phenomenon of power transmission.*

It should be noted that the 13th edition has deleted this entry, as this excellent description has been replaced by more "up to date material"! As engineers, academics and scientists, are we interested in truth, or do we just pay lip service to it, justifying our actions as not wanting to rock the boat?

To challenge the status quo, to take on the establishment, takes courage, ability, energy and a certain amount of stubbornness. Ivor Catt has all of these qualities in abundance. Hopefully, time will afford him the recognition his contributions to science deserve.

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Battery and resistor. Steady state.

We start with a conventional view of a battery with voltage V connected via two uniform perfect conductors to a resistor R (Fig.1).

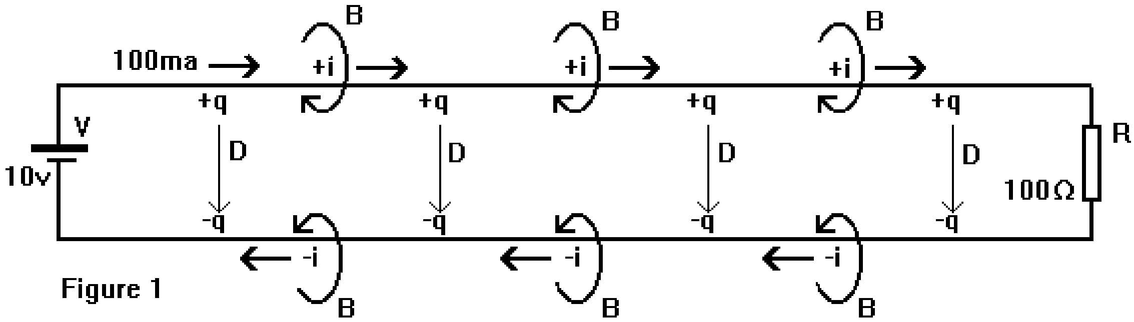

Figure 1

A steady current flows round the circuit, through battery, conductors and resistors. Ohm's Law tells us that the voltage equals the current multiplied by the resistance. Therefore the current is $I = V/R$. Every point on the surface of the upper conductor is at potential V, and every point on the surface of the lower conductor is at a zero potential.

The space between the two conductors, shown in cross section (Fig. 2), is filled by tubes of electric displacement D.

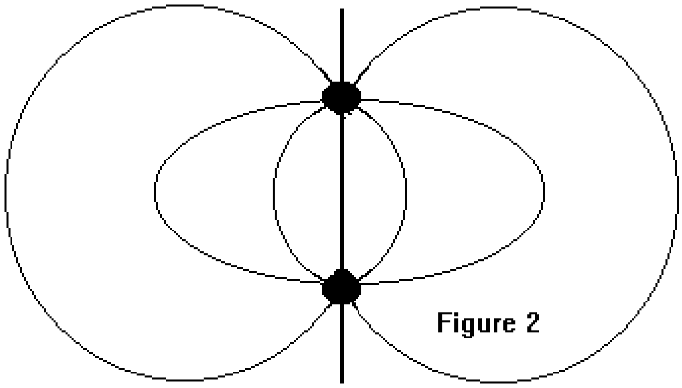
Figure 2

Each tube of electric displacement terminates on unit positive charge on the upper conductor and unit negative charge on the lower conductor [1]. If the capacitance between the two conductors is C, then the total charge on each conductor is given by $Q= CV$. If the capacitance per unit length is c, then the total charge per unit length on each conductor is $q=cV$

The energy stored in the electric field between the conductors is

$$U_d = \frac{1}{2} CV^2 \quad \text{(Ref. 1), or}$$

$$u_d = \frac{1}{2} cV^2 \quad \text{per unit length.}$$

The space between the two conductors is filled by tubes of magnetic flux which encircle the current in the conductor.

If the self inductance of the pair of conductors is L, then the total magnetic flux passing between the conductors is

$$\Phi = L\,I\,.$$

If the self inductance per unit length is l, then the magnetic flux per unit length is

$$\phi = l\,I$$

The energy stored in the magnetic field created by the current in the two conductors is

$$U_b = \frac{1}{2} L\,I^2, \text{ or}$$

$$u_b = \frac{1}{2} l\,I^2 \quad \text{per unit length (ref. 2)}$$

Power is delivered by the battery into the circuit at a rate of watts which is the product of voltage and current VI. The

resistor absorbs power at the same rate, turning electric power into heat, which then radiates from it.

The energy trapped in the fields between the conductors totals

$$U_d + U_b = \frac{1}{2} CV^2 + \frac{1}{2} L I^2 \quad (1)$$

The energy stored in each unit length is

$$u_d + u_b = \frac{1}{2} cV^2 + \frac{1}{2} l I^2 \quad (2)$$

Battery and resistor. Initial state.

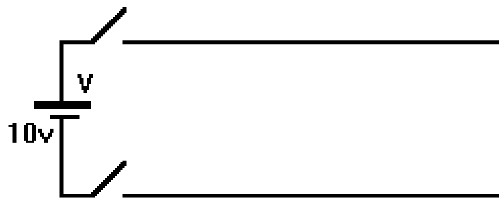

Figure 3

Now let us turn to the conventional view of the initial conditions. We will insert two switches, one in the top conductor and one in the bottom conductor (Fig.3). When we close the two switches, the distant resistor cannot define the current which rushes along the wires because the wave front has not yet reached the resistor (Figs.4,5).

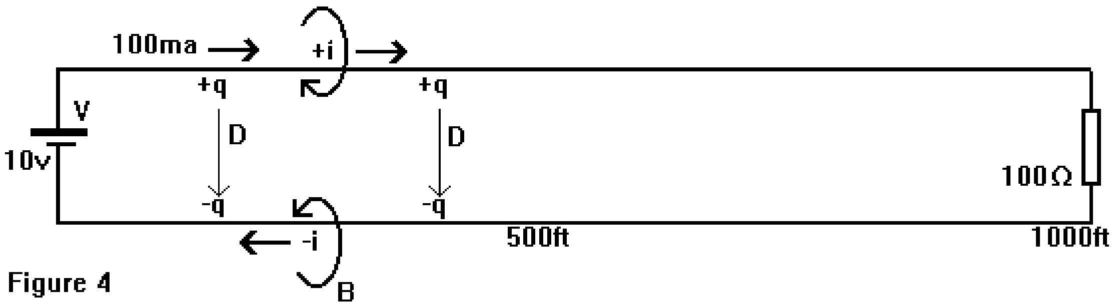

Figure 4

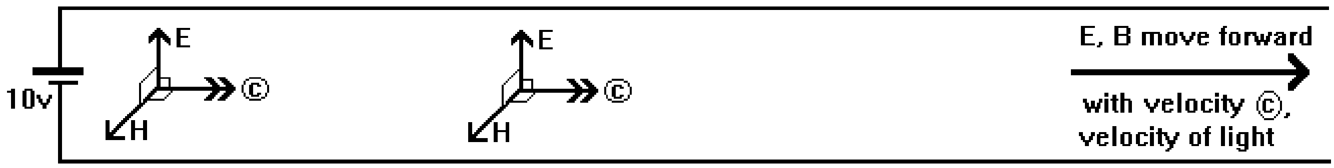

Figure 5

Lacking knowledge of the value of the resistor, the current is defined by the characteristic resistance Z_0 of the pair of conductors (usually called their characteristic impedance). Thus,

$$\frac{V}{I} = Z_0 \, .$$

So the instantaneous current is

$$\frac{V}{Z_0} \, .$$

Instead of delivering this power to the resistor, the battery delivers it into the space between the conductors for the first few nanoseconds. The wave front travels to the right at the speed of light for the vacuum ***C***. In our case, where the resistor is at a distance S from the battery, the wave front reaches the resistor after a time S/***C***. During this initial time, the battery supplies the energy necessary (eqn.1) to set up the electric and magnetic fields in the space between the conductors. The energy delivered by the battery during the time S/***C*** when the wave front travels from battery to resistor is VI S/***C***.

The characteristic resistance is

$$Z_0 = \sqrt{\frac{l}{c}} \quad \text{(Ref. 3)} \quad (3)$$

Simple algebra will show that in the initial (transient) case, electric and magnetic energy are equal (to u_1), as follows.

The energy in the electric field is

$$\mathbf{u_d} = \frac{1}{2} cV^2 \quad \text{(Ref. 1)}$$

Now

$$\frac{V}{I} = Z_0 \quad (\text{ i.e. } V^2 = I^2 {Z_0}^2)$$

We can rewrite

$$\frac{1}{2} cV^2 \text{ as } \frac{1}{2} cI^2 {Z_0}^2$$

Now substitute

$$\frac{l}{c} \text{ for } {Z_0}^2 \quad \text{(eqn.3)}$$

and we get

$$\frac{1}{2} l I^2 = (u_b),$$

the energy in the magnetic field.
Therefore

$$u_d = u_b = u_1$$

Now let us show that the energy (which we shall call $2u_2$) delivered by the battery in time $1/\boldsymbol{C}$ equals the energy stored in the fields ($2u_1$) in a section of unit length. Power from the battery is VI. One second's worth of this power charges up a length $\boldsymbol{C}$. So the energy stored in unit length is

$$2u_2 = \frac{VI}{C},$$

where $\boldsymbol{C}$ is the velocity of light. But we know that

$$C = \frac{1}{\sqrt{lc}} \quad \text{(Ref. 4)}$$

So VI/$\boldsymbol{C}$ becomes

$$VI\sqrt{lc}$$

Substitute for I using the formula

$$I = \frac{V}{Z_0},$$

to give

$$2u_2 = \frac{V^2}{Z_0} \sqrt{lc}$$

Then using the formula (3) for Zo we end up with

$$2u_2 = cV^2,$$

which is twice the energy

$$u_d \left(= \frac{1}{2} cV^2\right)$$

in the electric field. Therefore

$$2u_1 = 2u_2 \; (=2u)$$

If the terminating resistor is equal to the transmission line's characteristic impedance, then there is no reflection. The battery thinks the transmission line has infinite length. It continues to deliver power at the initial rate.

Unterminated transmission line.

If the resistor is missing, then all of the energy travelling to the right at the speed of light is reflected and begins the return journey to the left.

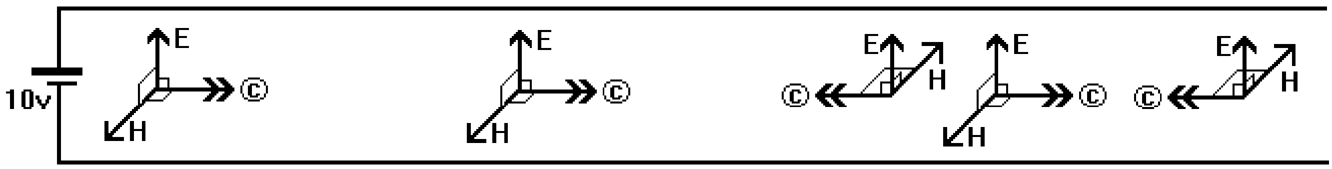

Figure 6

Let us consider the case where the line length is S, and time 3S/2$\boldsymbol{C}$ has elapsed since the switches were closed (Fig.6). The field situation in the first half is as before, the energy per unit length being VI/$\boldsymbol{C}$; half of it

$$u = \frac{1}{2}\frac{VI}{C}$$

in the electric field and half in the magnetic field. In the last half, a returning wave front of equal energy density is superposed on the energy making its outward journey. Magnetic fields cancel out, and the second half appears to be a steady charged capacitor, charged to an amplitude 2V. Our formula

$$U = \frac{1}{2}cV^2$$

is thought to give us the electric field's energy per unit length. Since the voltage has doubled, the energy appears to have quadrupled to

$$\frac{1}{2}c(2V)^2 = 2cV^2 = (4u)$$

instead of the

$$\frac{1}{2}cV^2 \quad (= u)$$

associated previously with the single electric field. Thus, double the electric field has led to four times the energy because the formula for energy contains the square of the voltage. This quadrupling is untrue, because the two electric fields, one travelling to the right and the other to the left, have no relationship with each other. The reality is that each electric field contains energy u per unit length, totalling 2u, not 4u, of electric energy. The missing energy is contained in the invisible magnetic fields. These are invisible because the leftwards travelling magnetic field makes the equal rightwards travelling magnetic field invisible to our measuring instruments. Thus, in the last half, the energy per unit length is made up as follows; u in the forward travelling electric field, u in the forward travelling magnetic field, u in the backward travelling electric field, and u in the backward travelling magnetic field. It is a mathematical accident that we get the correct answer for total energy when we wrongly think that the last half of the transmission line is steadily charged with electric field, and no magnetic field exists. Pace our calculations, the total energy density from electric fields is 2u not 4u.

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[1] This is Gauss's Law, which later became one of Maxwell's Equations.

Battery and resistor. Steady state. Numerical values.

We start with a conventional view of a 10 volt battery connected via two uniform conductors to a $100\ \Omega$ resistor (Fig.1).

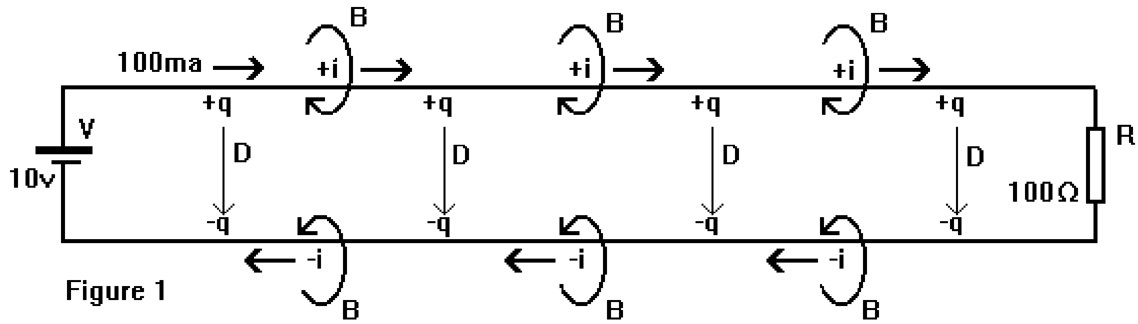


Figure 1

A steady current flows round the circuit, through battery, conductors and resistors. Ohm's Law tells us that the voltage equals the current multiplied by the resistance. Therefore the current is

$$\frac{10}{100}\ \text{amp} = 100\ \text{ma}$$

Every point on the surface of the upper conductor is at a potential V of 10v, and every point on the surface of the lower conductor is at a potential of 0v.

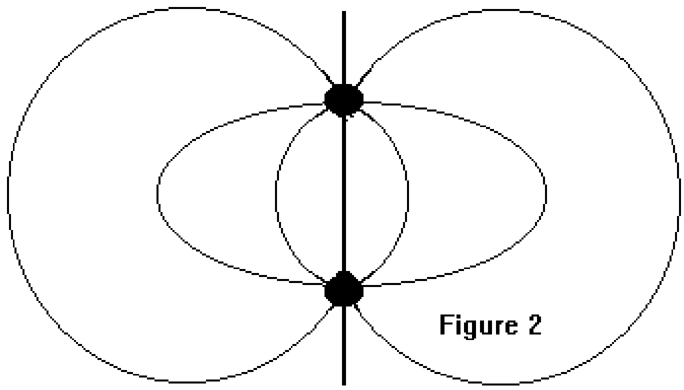


Figure 2

The space between the two conductors, shown in cross section (Fig.2), is filled by tubes of electric displacement D. Each tube of electric displacement terminates on unit positive charge on the upper conductor and unit negative charge on the lower conductor [1]. If the capacitance between the two conductors is C, then the total charge on each conductor is given by Q = CV. If the capacitance per foot is c, then the charge per foot is q = cV.

The energy stored in the electric field between the conductors is

$$\frac{1}{2}\,CV^2\ \text{(Ref. 1), or}\ \frac{1}{2}\,cV^2\ \text{per unit length.}$$

The space between the two conductors is filled by tubes of magnetic flux which encircle the current in the conductor.

If the self inductance of the pair of conductors is L, then the total magnetic flux passing between the conductors is $\Phi = L\,I$. If the inductance per unit length is *l*, then the magnetic flux per unit length is $\phi = l\,I$.

The energy stored in the magnetic field created by the current in the two conductors is

$$\frac{1}{2}\,L\,I^2\ \text{(Ref. 2), or}\ \frac{1}{2}\,l\,I^2\ \text{per unit length.}$$

Power is delivered by the battery into the circuit at the rate of watts which is the product of voltage and current. This

equals 10v x 100ma = 1 watt. The resistor absorbs energy at the same rate, and turns 1 watt of electric power into heat, which then radiates from it.

The energy trapped in the fields between the conductors totals

$$\frac{1}{2}\,CV^2 + \frac{1}{2}\,L\,I^2 \quad (1)$$

The energy stored in each unit length is

$$\frac{1}{2}\,cV^2 + \frac{1}{2}\,l\,I^2 \quad (2)$$

Battery and resistor. Initial state.

Now let us turn to the conventional view of the initial conditions. We will insert two switches, one in the top conductor and one in the bottom conductor (Fig. 3).

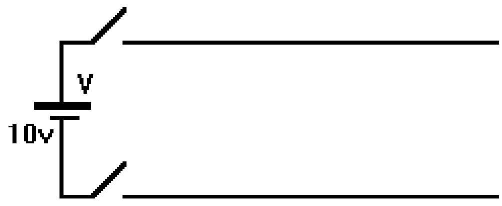


Figure 3

When we close the two switches, the distant resistor cannot define the current which rushes along the wires because the wave front has not yet reached the resistor (Figs.4,5.)

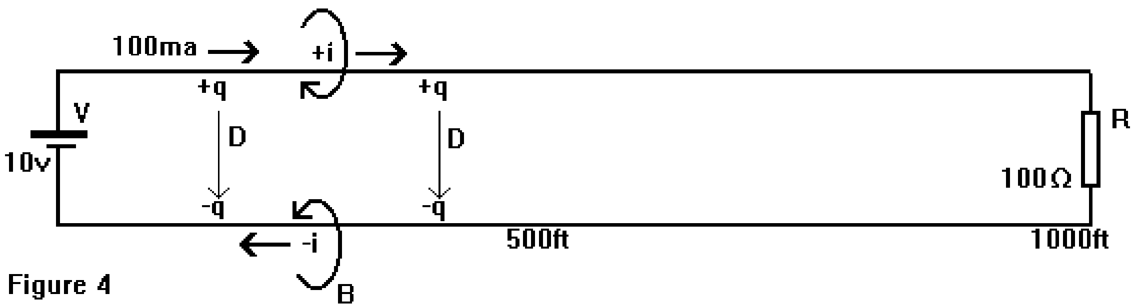


Figure 4

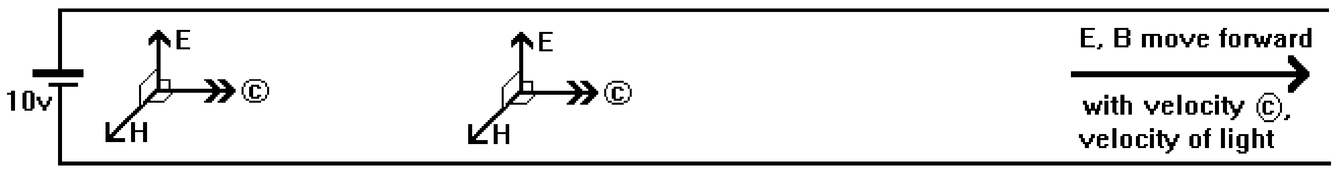


Figure 5

Lacking knowledge of the value of the resistor, the current is defined by the characteristic resistance Z_0 of the pair of conductors (usually called their characteristic impedance. Thus, $\frac{V}{I} = Z_0$.)

In the case of the cross section shown (Fig.2), let us assume this is about $100\ \Omega^2$. So the instantaneous current is 100ma. Instead of delivering the 1w (=1J/s) of power to the resistor, the battery delivers it into the space between the conductors for the first few nanoseconds. The wave front travels to the right at the speed of light for the vacuum, that is, one foot per nanosecond [2]. In our case, where the resistor is 1000 feet from the battery, the wave front reaches

the resistor after $1\mu sec$. During this initial $1\mu sec$, the battery supplies the energy necessary (eqn.1) to set up the electric and magnetic fields in the space between the conductors. The energy delivered by the battery during the $1\mu sec$, when the wave front travels from battery to resistor is VIt, where t is $1\mu sec$. This equals $1\mu J$, or 1nJ per foot.

The energy per foot in the electric field is $\frac{1}{2}cV^2$,where c is the capacitance per foot between the conductors. For a $100\,\Omega$ line, this is $10\ pF^3$, resulting in energy of about $\frac{1}{2}$ nJ . The energy per foot in the magnetic field is $\frac{1}{2} l I^2$, where *l* is the self inductance of the loop formed by one foot length of the two conductors. The inductance is about 100nH [3], resulting in energy of about $\frac{1}{2}$ nJ .

The characteristic resistance is

$$Z_0 = \sqrt{\frac{l}{c}} \ . \quad \text{(Ref. 3)} \quad (3)$$

The above calculations showed that in the initial (transient) case, electric and magnetic energy are equal. Simple algebra will give the same result, as follows;

The energy in the electric field is

$$u_d = \frac{1}{2} cV^2.$$

Using the formula

$$\frac{V}{I} = Z_0 \text{ , which means that } V^2 = I^2 Z_0^{\ 2},$$

and we can rewrite

$$\frac{1}{2} cV^2 \quad \text{as} \quad \frac{1}{2} c\, I^2 Z_0^{\ 2} \cdot$$

Now substitute

$$\frac{l}{c} \text{ for } Z_0^{\ 2}$$

and we get

$$\frac{1}{2} l\, I^2$$

the energy in the magnetic field. Each of these equals $\frac{1}{2}$ nJ per foot.

Power from the battery is VI. One second's worth of this power would charge up 10^9 feet of cable, because the velocity of propagation ***C*** is 10^9 feet per second. So the energy stored in one foot length is U = VI/***C*** = 1nJ. So the energy delivered by the battery in 1 nsec equals the energy stored in the fields in a section one foot long.

If the terminating resistor is equal to the transmission line's characteristic impedance, then there is no reflection. The battery thinks the transmission line has infinite length. It continues to deliver power at the initial rate of 1 watt.

Unterminated transmission line.

If the resistor is missing, then all of the energy travelling to the right at the speed of light is reflected and begins the return journey to the left (Fig.6).

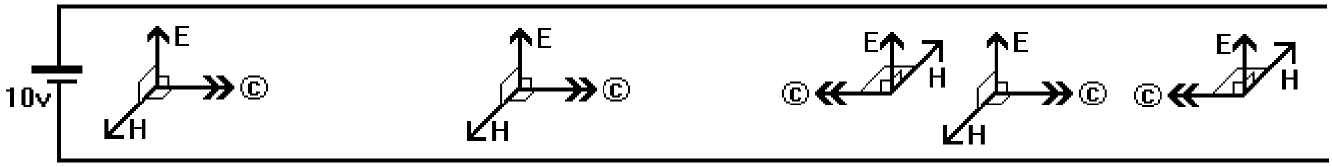


Figure 6

Let us consider the case where the line length is 1000 feet, and 1500 nsec have elapsed since the switches were closed. The field situation in the first 500 feet is as before, the energy being $\frac{1}{2}$ nJ per foot in the electric field and $\frac{1}{2}$ nJ per foot in the magnetic field. In the last 500 feet, a returning wave front of equal energy density is superposed on the energy making its outward journey. Magnetic fields cancel out, and we appear to have a steady charged capacitor 500 feet long, charged to an amplitude of 20 volts. Our formula

$$U = \frac{1}{2} CV^2$$

gives energy per unit length as before. Since the voltage has doubled, the energy appears to be 2nJ instead of the $\frac{1}{2}$ nJ associated previously with the electric field. Thus, double the electric field has led to four times the energy. This is untrue, because the two electric fields, one travelling to the right and the other to the left, have no relationship with each other. The reality is that each electric field contains $\frac{1}{2}$ nJ per foot, totalling 1nJ per foot. The missing energy is contained in the invisible magnetic fields, invisible because the leftwards travelling magnetic field makes the equal rightwards travelling magnetic field invisible to our measuring instruments. In the last 500 feet, the energy per foot is made up as follows;

$\frac{1}{2}$ nJ in the forward travelling electric field,

$\frac{1}{2}$ nJ in the forward travelling magnetic field,

$\frac{1}{2}$ nJ in the backward travelling electric field, and

$\frac{1}{2}$ nJ in the backward travelling magnetic field.

It is a mathematical accident that we get the correct answer for total energy when we wrongly think that the last 500 feet are steadily charged with

electric field, and no magnetic field exists. Pace our calculations, the total energy density from electric fields is 1nJ not 2nJ.

---

[1] This is Gauss's Law.

[2] See Ref.3a, pp 5 and 8 (eqn.3.5);

$\boldsymbol{C}$=1/(Ã–$m_o e_o$)=1/(Ã–lc). Also p.95.

[3] ibid, $2l = 0.4 \ln(a/r)$ mH/m, giving us about 100nH/ft.

(I write $2l$ not l because there are two conductors.)

The Pulse.

This time, we will close the switches and open them again after 1 microsecond. Since the wave front travels 1000 feet in $1\mu sec$, it has reached the open circuit at the end at the moment when the switches reopen.

$\frac{1}{2}\mu sec$ later, when the pulse is as in Figs.7,8, we open two new switches in the centre of the lines.

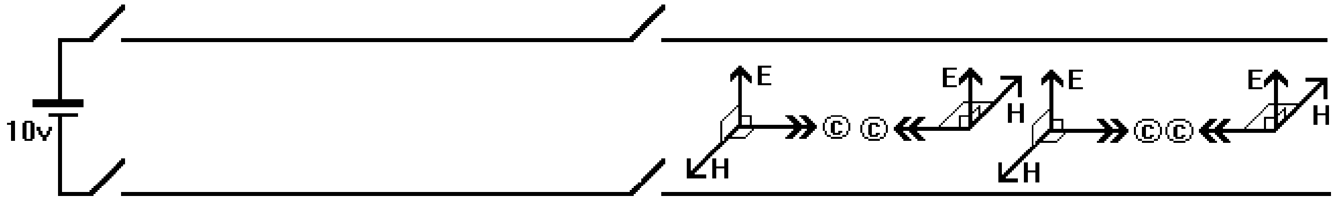


Figure 7

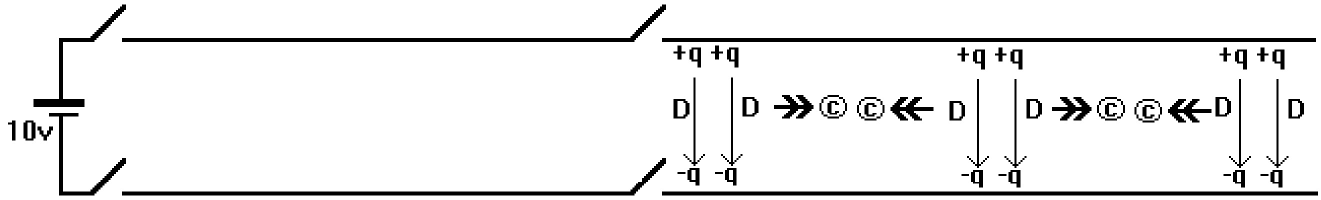


Figure 8

All the energy is now trapped in the right hand 500ft, which appears to become a steady charged capacitor with voltage 20v and no magnetic field.

However, we know that this is an illusion, because

a) if at any time we close the central switches, the energy current [1] proceeds towards the left;

b) there is no mechanism for the reciprocating energy current to slow down. The reciprocating process is loss-less [2] (so that dispersion does not occur).

The Capacitor.

The whole of the foregoing argument remains valid if the two conductors are large flat parallel plates. Therefore the second half in Figures 7, 8 are indistinguishable from a rectangular charged capacitor. The fact that a capacitor has a medium other than vacuum does not affect the theory, since a transmission line may contain a dielectric material. The cross section of the two conductors, Fig.2, is irrelevant to the argument, and the conductors might equally well be rectangular, making the second half of Figs.7,8 a conventional charged capacitor.

The difference is that in our capacitor, a TEM wave vacillates from end to end of the capacitor plates, and there is no mechanism for it to slow down.

Ockham's Razor, "Entities are not to be multiplied beyond necessity" [3], tells us that the scientifically correct theory is the simplest theory which explains the observables. Now we have seen that the new contrapuntal model for the charged capacitor is necessary to explain the situation described above and pictured in

Figures fig3, fig4, fig5, fig6, fig7 and fig8. This new theory also explains all the effects

covered by the old model [4]. It follows that either the traditional theory for the charged capacitor must in future be rejected, or Ockham's Razor must be rejected by the scientific community.

Let us summarize the argument which erases the traditional model;

a) Energy current can only enter a capacitor at the speed of light.

b) Once inside, there is no mechanism for the energy current to slow down below the speed of light.

c) The steady electrostatically charged capacitor is indistinguishable from the reciprocating, dynamic model.

d) The dynamic model is necessary to explain the new feature to be explained, the charging and discharging of a capacitor, and serves all the purposes previously served by the steady, static model.

e) The static model, since it requires electric charge, collides with the Catt Anomaly.

The spherical capacitor, the square capacitor.

We start with a capacitor made up of two concentric spherical conductors close together (Ref.7). Their radii are a and (a+d). The capacitance is

$$C_0 = 4\pi\varepsilon a \frac{a+d}{d}$$

Now let us cut out a small square section. This gives us a charged square capacitor.

$$C_{\square} = \frac{\varepsilon A}{d}$$

Previous sections show that the situation in a charged square capacitor must follow a new model, or else we must repudiate Ockham's Razor.

Again using Ockham's Razor, we have to impose our new model onto the full sphere if it works, which it does. We also have to excise the traditional model with its stationary electric charge on the spheres and electrostatic field in the space (dielectric) between the spheres.

Now we notice the hidden weakness in our new model for the rectangular charged capacitor. Study of the battery, switches and transmission line (Figs.3thru8: fig3, fig4, fig5, fig6, fig7 fig8) led us to conclude that a so-called steady charged capacitor is not steady at all. Necessarily, a TEM wave containing (hidden) magnetic field as well as electric field is vacillating from end to end.

Common sense tells us that our new model applies to the square capacitor as well as the rectangular capacitor.

If we charged the square capacitor by delivering energy down the west side, we have to decide whether it would behave exactly the same whether the energy is later extracted from the same west side or from the north or south side. Common sense (and Ockham's Razor) tells us that the capacitor's response will be the same. That is, the square capacitor does not remember which was the edge through which energy was delivered into it.

It follows that, to the assertion that a TEM wave continuously vacillates from west to east, we must add the assertion that a TEM wave vacillates from north to south. Possibly the total velocity of propagation is not *C* but $C\sqrt{2}$, and the behaviour of the energy current is something like the Huygens model for light propagation (Ref.8).

The isolated, charged sphere.

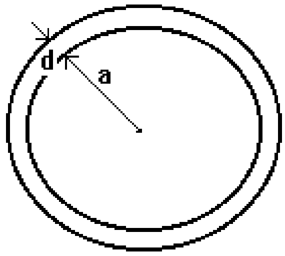


Figure 9

We reverse the picture (Fig.9) so that we start with negative charge on the inner sphere (and positive charge on the outer sphere). If we increase the outer radius (a+d) to infinity, $(a + d) \approx d$. We find that the capacitance does not decrease to zero, but to

$$C_o = 4\pi\varepsilon_0 a.$$

If a=1cm, C ≈ 1pF (Ref.7).

This leaves us with an isolated negative charge[5].

The electron.

We have seen that energy current travels around the isolated charged sphere. Each unit of energy current is matched by an equal amount travelling through it in the opposite direction, so that the total electric current and therefore i^2R losses in the sphere are zero.

The next step is to reduce the diameter of the inner sphere. If the total (negative) charge is kept constant, the energy in the surrounding field increases towards infinity. When a = 0, the energy is infinite while the charge is finite. Note that the energy (current) is concentrated near the centre, but extends throughout space (because the outer sphere which terminates the lines of electric flux is at infinity). This echoes Faraday's idea that unit charge extends throughout space (and is merely concentrated at a point). Total electric current on the suface of the disappearing inner sphere remains at zero. If this were the true model for the electron (and for other elementary particles), the fact that it contained infinite energy would explain the near-indestructability of fundamental particles, in the same way as it is more difficult to destroy an elephant than a gnat.

Two concentric conducting spheres were charged up. A square section was cut out. This became a charged square capacitor. In the latter, Occam's Razor says that under the contrapuntal model for a charged capacitor, energy current will be reciprocating, not only between west and east edges, but simultaneously between north and south edges, in a manner not fully understood by us.

We then increased the radius of the outer sphere to infinity, and the capacitance did not drop to zero. This became out model for the electron.

Consider instead an array of concentric spheres, charged such that (Theory N) the negative charge on one (outer) face of any one sphere equals the positive charge on the other (inner) face, leading to zero net charge.

As before, energy current travels in a great circle between any pair of spheres, with equal energy current travelling in the opposite direction. However, note that, due to the increasing radius between pairs of spheres, the energy current trapped between two outer spheres, having to travel further, falls behind that trapped between two inner spheres. All the same, the electric current and electric charge on the two faces of a particular sphere cancel, so that the sphere may be removed without changing the situation.

This enhancement of the model for the electron occurred to me some years ago. All energy current travels at 300,000 km/sec.

[1] Oliver Heaviside devised the term "Energy Current" (Ref.5) for the TEM pulse which travels down a transmission line guided by two conductors. It is also called the "Poynting Vector" and usually given the value EHsinq, where q is the angle between the direction of E and the direction of H. However, since in our theory E and H are always at right angles to each other, the Poynting Vector is simply EH.

[2] Since forward and returning waves have equal and opposite electric currents, resistive (I^2R) losses do not occur (even if the conductors are imperfect).

[3] "Entia non sunt multiplicanda praeter necessitatem."

[4] The traditional, old, theory for the charged capacitor is that static electric charge resides on the inside surfaces of the plates, and electrostatic field sits between the plates. There is no magnetic field.

The old, static theory cannot explain the situation outlined in figures 3 thru 8.

Further evidence against the old model is that the 'charging' of such a device can only be achieved by energy being fed in via a transmission line at the speed of light, since TEM waves cannot travel in a transmission line slower than the speed of light (p15, col.3).

[5]Actually, see Ref. 7, the argument should start with the isolated sphere and end with concentric spheres. However, the reversal illustrates the new model for an electron.

Interacting TEM waves.

Generally the interaction of two TEM waves is thought to be covered by Maxwell's Equations. However, I have shown (Ref.9) that this is not so. Maxwell's Equations contain only;

(1) the velocity of propagation of the TEM wave $c = \frac{1}{\sqrt{\mu\varepsilon}}$ and

(2) the impedance of the medium $\sqrt{\frac{\mu}{\varepsilon}}$.

They contain no additional information about electromagnetism in general, let alone information on the way two colliding TEM waves interact. Even more curiously, the empirical laws governing reflection at a resistively terminated transmission line seem to be a body of knowledge divorced from Maxwell's Equations.

Partial reflection in a transmission line.

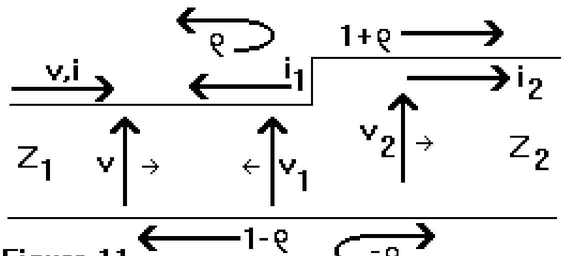


Figure 11

It is found experimentally that if a TEM wave travels down a uniform transmission line Z_1 (Fig.11) joined to a different transmission line Z_2 , some of the energy current reflects at the discontinuity and some continues (Ref.10). The voltage reflection coefficient is found to be

$$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1} .$$

In particular, if a pulse V travelling down a $100\ \Omega$ transmission line at the speed of light collides into a $300\ \Omega$ termination made up of three $100\ \Omega$ resistors in series, then a $\frac{1}{2}V$ pulse reflects and $\frac{3}{2}V$ dissipates across the termination; ($\frac{1}{2}V$ in each $100\ \Omega$ resistor).

The front end of a long $100\ \Omega$ transmission line looks exactly like a $100\ \Omega$ resistor. The situation remains the same in Figure 12;

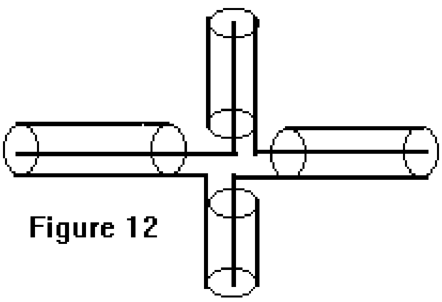


Figure 12

three downstream coaxial cables connected in series, mimicking the three $100\ \Omega$ resistors, and also (Fig.13) a parallel plate transmission line delivering the pulse into three such lines in series.

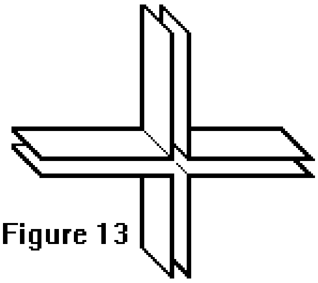


Figure 13

Our next step is to widen the parallel plates to infinity, and this gives us our simplest situation for analysis (Fig.14). Having reached this stage, we can set out to gain the broader insights which our experimental knowledge of reflection in transmission lines gives us.

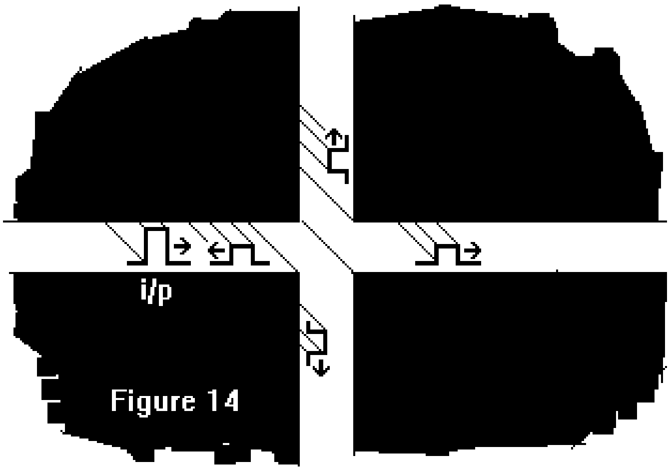
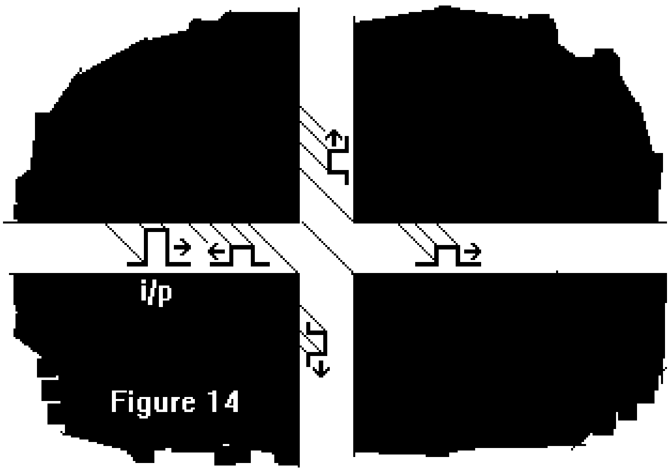


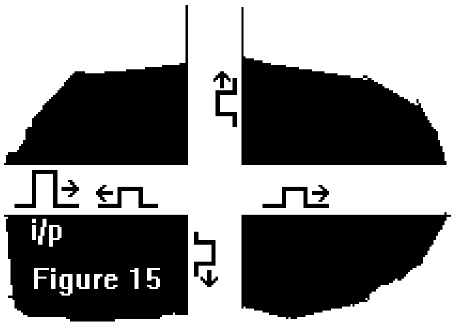
Figure 14

(Consideration of conservation of energy and also that the voltage across the discontinuity must be continuous lead us to the same formula for the reflection coefficient.)

Interaction between TEM pulses.

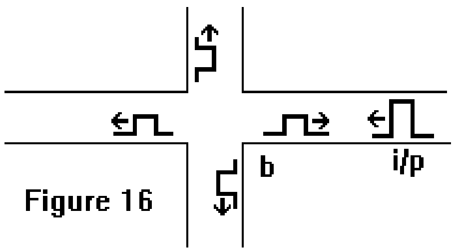


We start with an infinitely wide input (i/p) pulse delivered at the speed of light between perfectly conducting parallel plates into a four way split (Figs.14,15).



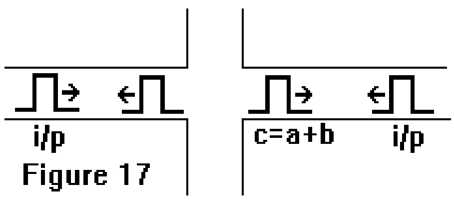
The i/p pulse splits up into four half sized pulses as shown. (Energy is conserved because energy is proportional to v^2 .)

A pulse coming from the east will behave similarly (Fig.16).



Experience shows that superposition applies for pulses travelling down transmission lines[1].

Dissimilar pulses.



Send two pulses towards a junction (Fig.17). These pulses are called 'dissimilar' for reasons which will

become clear[2]. The west pulse ('west wind') breaks up into the four pulses as shown in Figure 15. The east pulse breaks up similarly as in Figure 16. The combined result is that pulses exiting north and south cancel. Pulses exiting west and east add. Thus, dissimilar pulses help each other across the gap.

Dissimilar pulses hug.

Similar pulses.

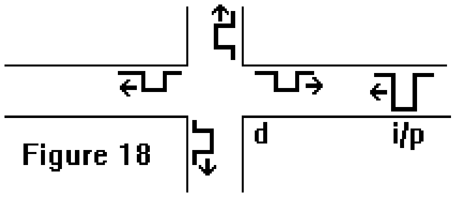


Figure 18

Now consider the case when the east pulse is negative. The result is that pulses exiting east and west cancel, while pulses exiting north and south add.

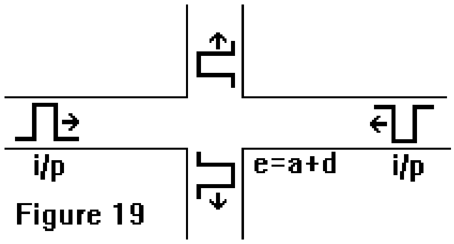


Figure 19

Our model for the behaviour of TEM pulses and their interaction is not disputed. It is unfamiliar because of the gulf between academic electromagnetic theory, which is awash with complex mathematics, and the practical engineering of high speed logic systems. When assembling high speed logic systems, I necessarily investigated and ruminated on the situations discussed above. However, any academic who investigated the subject would come to the same conclusions about the interaction of pulses.

We are now in a position to develop our thoughts in two directions; the car headlight beam and the structure of the crystal.

The car headlight.

As previously asserted (Ref.9), Maxwell's Equations give us no information beyond the numbers 300,000 and 377. Into that knowledge void enters the situation above where dissimilar pulses hug.

We also know that a pulse P1 which departs from the open circuit end of a transmission line reflects back towards the line[3]. If this returning pulse were followed by a (positive) pulse P2, then being dissimilar, they will hug. Therefore an alternating (perhaps sinusoidal) sequence of TEM pulses attempting to exit from the end of a transmission line will be helped in its forward progress by the portions of earlier (downstream) cycles recoiling (returning) back towards the source[4].

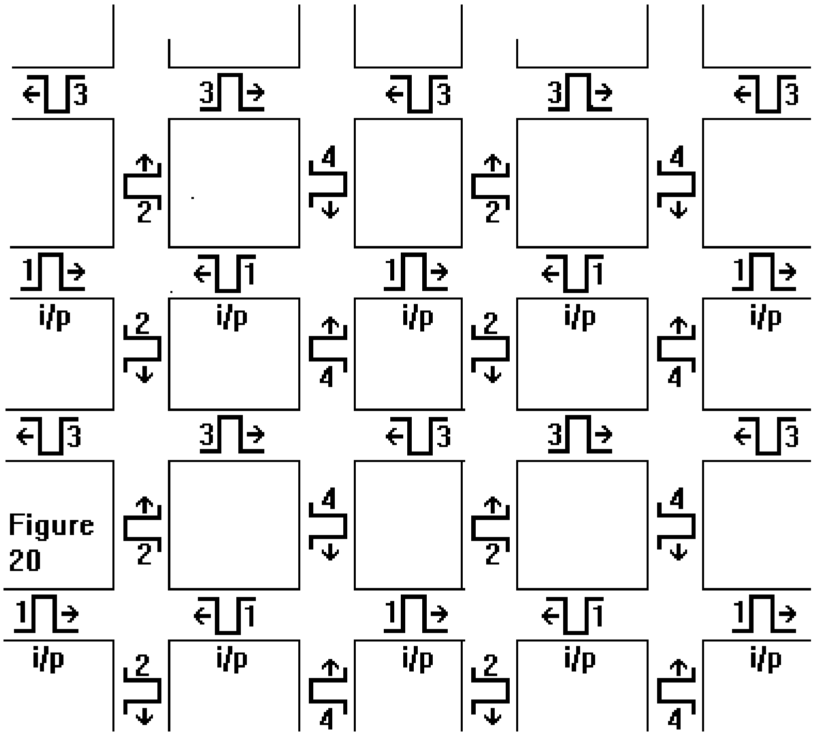
Synthesis.

The question arises as to the merits of the above model compared with other models for the car headlight beam. However, first we have to discover the other models. Do they exist in any coherent form?

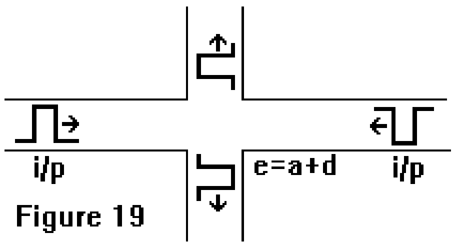
My impression is that competing models, if they exist, are hopelessly immersed in arcane mathematics and 'Modern Physics', which includes wave-particle dualism, the photon, and so on. There is no real competitor

for the model/theory above for the car headlight beam[5].

The Crystal.



In our attempt to build the interior of a crystal (Fig.20) we concatenate an array of Figures 19.



Whenever a pulse reaches a junction, it splits into two half pulses, each of which continues at right angles to the incident direction, accompanied by half of the colliding pulse. A subsidiary model for the flat surface (or edge) of our crystal is compatible. When a pulse attempts to exit from a transmission line it reflects without inversion (generating gravity by inspecting a nearby crystal). This indicates the possibility that a second superposed array of pulses which travel in the opposite direction, may be passing along the same array of paths shown. The sum of electric currents on the surfaces of the squares is thus zero, leading to zero I^2R losses. (This means that the {copper?} surface need not exist.) The pulses in the second array, being dissimilar, might hug the pulses in the first array, and so not interfere. The only effect of the second array is to reduce I^2R losses to zero, and so enable us to get rid of the conducting surfaces.

Note that at the start, we may have only pulses (1), which then circulate around the squares in time periods 1,2,3,4. Alternatively we may start off with pulses (1) and (3), which chase each other round the squares. And so on.

Difficulties with the Crystal Model.

1) We live in a 3D universe, and a crystal is 3D. The above model is only 2D. This leads us to our second system. Whereas all of the above was premised on a transmission line terminated by three resistors in series,

we can develop an equivalent scenario where those terminating resistors are in parallel. However, the reader is advised to keep the above system central in his mind, and regard what follows as merely subsidiary.

The perforated capacitor.

Following Figure 11, we moved to Figure 12, where a pulse travelling down a transmission line was confronted by three lines in series. We see another example in Figure 13 and beyond. In this section we address the inverse situation, which is closer to the reality of the charged capacitor.

Figures 12 and 13 become figures 21 and 22, where the path splits into three paths in parallel.

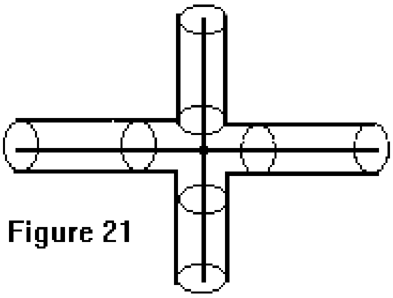


Figure 21

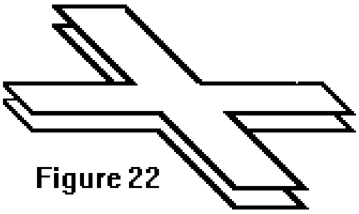


Figure 22

Under this new parallel regime;

Dissimliar pulses repel.

Similar pulses hug.

We first construct a capacitor with an array of square holes in it, and then reduce the size of the holes to zero. We will thus begin to see how the energy current vacillating across a charged capacitor travels both east-west and north-south at the same time.

Summary of interactions.

Definitions.

Driving into three resistors in series is called a series split (Fig12etc.).

Also called vertical.

Driving into three resistors in parallel is called a parallel split (Fig.21etc.).

Also called horizontal.

For a series split, dissimilar pulses hug and similar pulses repel.

For a parallel split, dissimilar pulses repel and similar pulses hug.

---

[1]

However, the curious exception is in the matter of forces, which suddenly appear when TEM waves are superposed, see my letter in Electronics and Wireless World, feb85. Also Ref.18(b), p166.

[2]

The situation is essentially one in the style of Polar Co-ordinates. A 'positive' voltage is positive in a clockwise direction.

[3]

Figure 11 shows how any change of characteristic impedance in the space ahead of a pulse causes part of the pulse to reflect. When a pulse attempts to exit from the end of a transmission line, it sees a rapid sequence of small changes in characteristic impedance as the cross section approached continues to change, each of these changes causing some of the pulse to reflect.

[4]

Light is of course a sinusoidal TEM wave, and so contains the requisite sequence of positive and negative pulses.

[5]

This is a good place to point out the clash between Bohr's Correspondence Principle (which says that after 1927 no spring cleaning in science is allowed) and Ockham's Razor, which says that unnecessary clutter must be jettisoned. The decision is based on loyalty not on logic, with the entrenched academic wanting to retain all his hard-learned clutter, and continue to earn good money teaching it, however obsolete. This is the deep meaning of Bohr's Correspondence Principle (Ref.11). If read honestly, T.S. Kuhn sides with William of Ockham. "Though logical inclusiveness remains a permissible view of the relation between successive scientific theories, it is a historical implausibility." (Ref.12).

Future developments.

An array of TEM waves which are mutually trapped (to form a crystal) appears to have ample degrees of freedom to enable it to construct a classic crystal with flat exterior surfaces composed of rows and columns of 'atoms'. It is regrettable that the intrusion of the particle, or photon, into an otherwise straightforward system with rich development potential should obstruct forward progress. The political compromise nearly a century ago which caused 'modern physics' to exploit the pedigrees of both wave theory and particle theory[1] has inevitably led to a sterile century with no development, and it blocks development today.

Keeping within the wave theoretical system, it is possible to explain why so-called 'particles' should appear to have equal size, although a totally wave theory appears to be scalable and therefore incompatible with the apparently recurrent electron and hydrogen particles with consistent size. One method would be to discuss the collision of two such particles, and the resulting energy/matter exchange. There are three possibilities. Either the larger steals from the smaller, or there is no transfer, or the smaller steals from the larger. The fact that there is more than one 'particle' in today's galaxy indicates that if a galaxy is very old, the first possibility must be wrong. The second possibility is unlikely. The third would fully explain the gradual equalizing out of 'particles' in a galaxy over time. (This approach only explains why all hydrogen particles are equal, and needs extension to explain the existence of more than one type of particle.)

The analogy between L, C and R.

In this chapter we develop a useful analogy which leads to simplified calculation in all cases and to a simple technique for measurement in those cases which do not yield to calculation.

We shall consider the special case of a parallel-plate transmission line (Figure 24). a<<b.

We shall discuss the resistance, capacitance and inductance per unit length of the line.

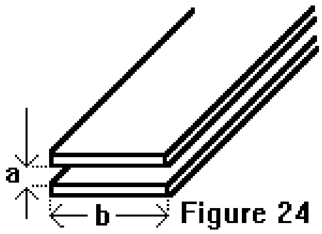


Figure 24

Resistance.

If the medium between the plates has resistivity ρ, then the resistance between the plates per unit length is

$$R_1 = \rho \frac{a}{b} = \rho f$$

where we have defined a/b as a geometrical factor which is a dimensionless function of the dimensions of the line[2].

Capacitance.

For a parallel-plate capacitor, the capacitance per unit length is

$$C_1 = \varepsilon \frac{b}{a} = \frac{\varepsilon}{f} .$$

Inductance.

For a parallel-plate transmission line, the self-inductance per unit length is

$$L_1 = \mu \frac{a}{b} = \mu f.$$

Note that the same geometrical factor f occurs in each case. This useful result holds not only in the case of parallel-plate geometries, but is true in general.

We now calculate the characteristic impedance Zo and velocity of propagation *C*.

$$Z_0 = \sqrt{\frac{L_1}{C_1}} = \sqrt{\mu f \frac{f}{\varepsilon}} = f\sqrt{\frac{\mu}{\varepsilon}}$$

$$C = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{\mu\varepsilon}}$$

Let us look first at the result for Z_0 . In the parallel-plate case we can substitute

$$f = \frac{a}{b}$$

to obtain

$$Z_0 = \frac{a}{b}\sqrt{\frac{\mu}{\varepsilon}}$$

In general we can obtain a value for Z_0 by noting the analogy between the equations for Z_0 and R_1 , where we note that the formula for Z_0 is the same as that for R_1 except that ρ has been replaced by $\sqrt{\frac{\mu}{\varepsilon}}$. This means that we can obtain the geometrical factor by calculating the resistance between the conductors and multiplying by the factor $\frac{\frac{1}{\rho}}{\sqrt{\frac{\mu}{\varepsilon}}}$. In cases where a calculation cannot be made, measurements using resistive paper can be used (Ref.15). Here the conductors are painted onto the resistive paper using conducting paint and the resistance between them measured with an ohmmeter. The equivalent to the resistivity is the resistance between two sides of a square of paper.

Note also that the velocity of a wavefront *C* is independent of the geometry, and is a property only of the medium in which the conductors are placed.

We shall use the results just derived to obtain the impedance of a co-axial line.

Impedance of a co-axial line.

The outwards resistance of a thin co-axial shell at radius r is

$$R_r = \rho \frac{\delta r}{2\pi r}$$

The resistance between inner and outer conductors for a unit length of cable is

$$R_1 = \int_a^b R_r dr = \frac{\rho}{2\pi}\int_a^b \frac{dr}{r} = \frac{\rho}{2\pi} \log_n \frac{b}{a}$$

Thus in this case, the geometrical factor is

$$f = \frac{\log_n \frac{b}{a}}{2\pi}$$

and therefore the impedance is

$$Z_0 = f\sqrt{\frac{\mu}{\varepsilon}} = \frac{1}{2\pi} \log_n \frac{b}{a}\sqrt{\frac{\mu}{\varepsilon}}$$

which is the standard result for the impedance of a co-axial line.

The L-C Model for the transmission line.

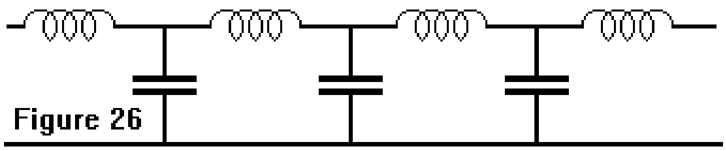


Figure 26

It is common for textbooks to represent a transmission line as shown in Figure 26. It is possible, on the basis of this model and making use of the Laplace transform to derive the equations of step propagation. However, this method has little to recommend it, especially since it appears to lead to a high frequency cutoff which is quite spurious. There is of course no high frequency cutoff inherent in any transmission line geometry. The only factor which can lead to high frequency cutoff is frequency-dependent behaviour in the dielectric. If the dielectric is a vacuum there is no high frequency cutoff.

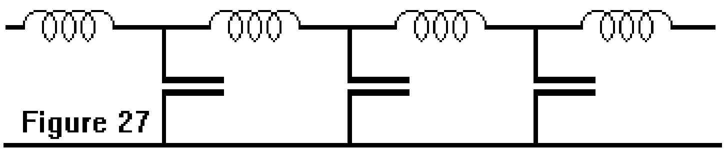


Figure 27

Malcolm Davidson has pointed out that since a capacitor is a transmission line (Ref.16), the model models a transmission line in terms of itself, which is absurd[3], see Figure 27.

The Transmission Line Reconsidered.

The traditional view is that when a TEM step travels down a two wire transmission line, it is bounded by electric current on each side and displacement current at the front. However, as well as advancing down the dielectric, the concept of skin depth tells us that it penetrates sideways into the conductors. We will however investigate the idea that the penetration into the conductors is of the same nature as the forward penetration down the dielectric, and no electric current is involved.

---

[1]

ignoring Einstein's opposition to the quantum. "... what the basic axioms in physics will turn out to be. The quantum or the particle will surely not be amongst them; ...." (Ref.14).

[2]

Before moving on to capacitance and inductance, we replace the resistive medium by a dielectric with infinite resistivity.

[3]

"Big fleas have little fleas
Upon their backs to bite 'em,
And these fleas have lesser fleas,
And so ad infinitum."

Historical background.

In the early nineteenth century electromagnetic theory made advances, a cornerstone of the theory being the doctrine of conservation of charge q, which developed into the doctrine of continuity of electric current flow dq/dt = i.

In the middle of that century Maxwell struggled with the paradox of the capacitor, where electric current entered one plate and then flowed out of the other plate apparently without traversing the space between the plates. It seemed that electric charge was being trapped on the upper plate and on the lower plate. Maxwell cut the Gordian knot (Ref.17) by postulating a new type of current, the extra current, as flowing across the gap between the capacitor plates so as to save the principle of continuity of electric current.

This extra current, later called 'displacement current', was a result of his postulation of 'electric displacement'. Maxwell said that the total outward displacement across any closed surface is equal to the total charge inside the closed surface.

Displacement current is sometimes explained as being the distortion of molecules in the dielectric, so that one end of the molecule is more positive and the other end is more negative. A difficulty arises if the dielectric is a vacuum, and has no molecules which could distort. So there have always been problems with displacement current. However, these are not the subject being discussed here.

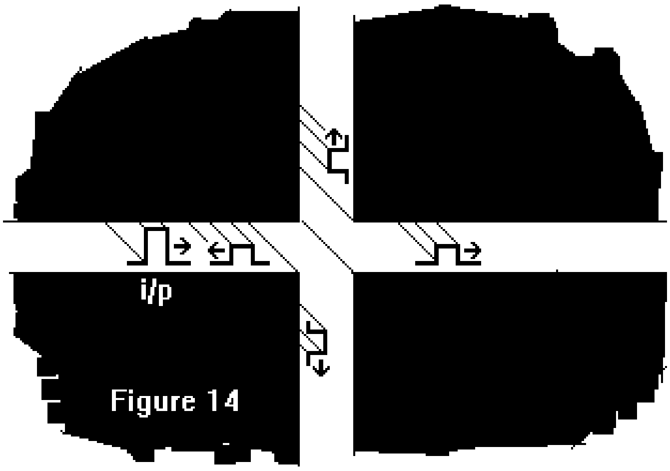
The Transmission Line.

In the 1870's the young Oliver Heaviside wanted to speed up digital (morse) signalling in a coaxial undersea cable between Newcastle and Denmark. He discovered that a Transverse Electromagnetic Wave travelled undistorted at the speed of light for the dielectric, between the inner and outer conductor. When such a voltage step reached half way to Denmark, a uniform closed circuit of currents was made up of electric currents down the conductors and an equal amount of displacement current across the front face of the advancing step. Thus, at every instant, Kirchhoff's First Law was obeyed.

We will discuss a new view of this combination of displacement current at the front face and electric current on the side of a TEM step travelling down a transmission line.

The Transmission Line Transmission Line.

In a uniform transmission line, the cross sectional shape of the two conductors and the vacuum between them determines Zo, the characteristic impedance of the line. Zo determines the ratio of voltage to current for any TEM signal delivered from the left into the line. Signals travel at the speed of light *C*.



If we deliver a 10 volt TEM step down a 100 ohm transmission line into a four way series junction (Fig.14), the signal breaks up into four signals travelling away from the junction. The amplitude of the four signals obeys the well known laws for a change in characteristic impedance (Fig.11)[1].

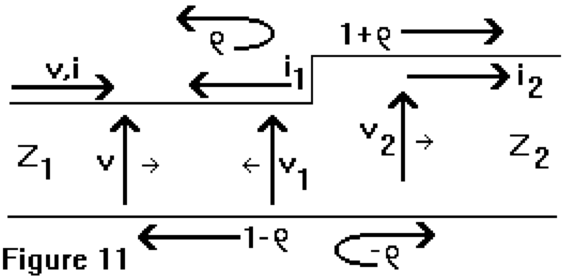


Figure 11

If the junction is of four identical transmission lines each with Zo=100 ohms, then the incident signal sees before it an impedance of 300ohms. The coefficient of reflection is

$$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{1}{2}$$

The result is that a half amplitude signal of 5v returns back to the left. Since at the junction we see both incident signal plus reflection across the input line, the total voltage at the junction is 15v. So a 5v signal must travel forward down each of the downstream transmission lines.

The incident power was V.1=10v x 100ma = 1 watt. The power in each of the four signals leaving the junction is 5v x 50ma = 250 mw. So energy is conserved.

Now let us consider the case where the top and bottom transmission lines are changed to a very small Zo=0.01 ohm [2]. The reflection coefficient becomes a negligible 0.02/200.02 = 0.0001 ohm, and a negligible 1mv reflects back to the left. A total of 10.001v forward signal is shared between the three downstream transmission lines. The big one receives 9.999v while each of the other two receive 1mv.

Let us introduce a second similar branching downstream to the right. This time, the incident signal of 9.999v (increased by the new 1mv reflection) splits up into forward going signals 1mv, 9.998v and 1mv.

At further branches downstream, (there is a further tiny reflection,) a tiny signal enters each of the branches, while a slightly reduced signal continues to the right.

The Dielectric Constant of Copper.

Consider three capacitors in series, each with plate area a, dielectric thickness d, dielectric constants $\varepsilon_1, \varepsilon_2, \varepsilon_3$. . The formula for the capacitance c of the three in series is given by

$$\frac{1}{c} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}$$

In each case, a term on the right becomes $\frac{d}{\varepsilon a}$.

If the 'dielectric' in the middle capacitor is copper, we know that the second term disappears, and $\frac{1}{c} = \frac{1}{c_1} + 0 + \frac{1}{c_3}$. This means that $\frac{d}{\varepsilon_2 a} = 0$. It follows that the dielectric constant for copper must be ∞ . [3]

The transmission line with resistive conductors.

Let us consider a transmission line with vacuum for dielectric and with characteristic impedance Zo=100 ohms. Its unusual feature is that instead of two copper conductors, it has very thin resistive conductors, where the resistance of each 1cm section of each conductor is 10mohm.

A 100v step is launched down the transmission line, in the vacuum between the two (resistive) conductors. During the first 30psec, when it traverses the first 1cm of the line, the 100v signal splits three ways, in the ratio 0.01 : 100 : 0.01. This means that a 99.98v signal arrives at the end of the first 1cm section, and proceeds to the right, through the vacuum dielectric. A 10mv step stays across the first 1cm of the upper conductor. A 10mv step stays across the first 1cm of the lower conductor.

During the second 30psec, the surviving 99.98v signal traverses the next 1cm of line, again splitting three ways, into 10mv, 99.96v and 10mv signals. Also, due to the 2mohm mismatch, a very small step reflects backwards up the line.

During the third 30psec, two more 10mv steps remain behind, while 99.94v proceeds to the right at the speed of light.

The transmission line with transmission line conductors.

The situation is much the same as before, except that, instead of having 1cm sections of resistive (10mohm) conductor, each 1cm of each conductor is replaced by the front end of a transmission line with characteristic impedance 10mohm.

This time, instead of each laggardly 10mv step lingering across its prescribed 1cm of resistive conductor, it advances at the appropriate speed (for the dielectric of the new, Zo=10 mohm transmission line) outwards, sideways from the direction of the main voltage step travelling through the vacuum.

The conductor which delineates the further face of the outwards transmission line for the first 1cm of line, and also the nearer face of the outwards transmission line for the second 1cm of line, is very thin. It turns out that the electric current down one face of the conductor is equal and opposite to the current down the other face. As the conductor's thickness is further reduced, these two currents merge, cancel, and losses drop to zero.

Velocity of propagation into this row of transission lines, each with Zo = 10 mohm, is lower if the dielectric in them has a higher dielectric constant, reaching zero if the dielectric constant is infinite.

[1]
Voltage and current must correlate at all times, and energy must be conserved. These requirements more or less prescribe the laws of reflection.

[2]
This very low Zo might be achieved by inserting a dielectric with very high dielectric constant, or by changing the function of geometry f (discussed above).

[3]
The reader may be amused by Carter's approach to this subject, Ref.3c, p265; "Nothing has been written in this book which would enable any meaning to be attached to the permittivity, k, of a metal; we must merely assert here that the value is not very different from unity."

Copper as a dielectric.

The situation is much the same as before, except that the Zo = 10 mohm transmission lines have their dielectric constant ε slowly increased to a higher and higher value. The effects are twofold; less of the incident 100v signal is left behind, to divert down the sideways transmission lines, and the velocity of propagation into these transmission lines decreases.

We finally reach the ultimate, copper, when

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}} = 0 \, ,$$

and propagation velocity $\frac{1}{\sqrt{\mu\varepsilon}}$ is zero.

Implications.

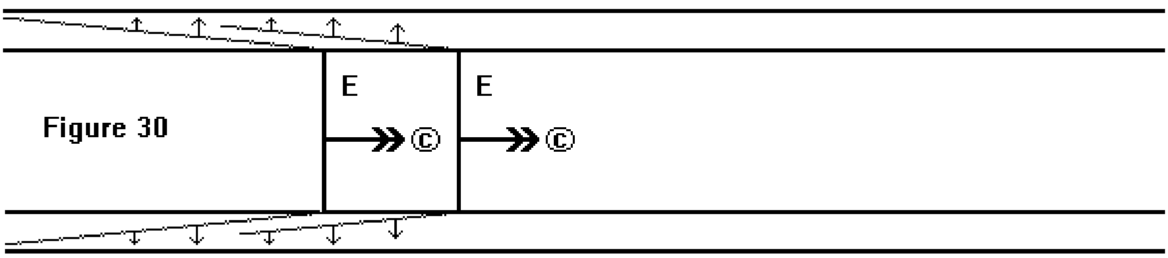


Figure 30

If a TEM step travels down in a dielectric between two conductors, no flow of electric current occurs in the conductors bounding the dielectric. To the extent that conductors are imperfect, part of the TEM step penetrates into them, but still no electric current is involved.

Electric current plays no part in the passage of a TEM step in the dielectric between two conductors. It is generally accepted that displacement current traverses the front face of the TEM wave (Fig.30). Now we see that it is displacement current only in the 'conductors' bordering the dielectric along which the TEM wave advances at high speed. These conductors are in fact dielectrics with very high ε . Ockham's Razor requires that we reduce the traditional dualistic system containing conductors as well as dielectrics to a unified system containing only dielectrics. We also have to exclude so-called 'electric current' from the process where energy travels from car battery to car headlight. Energy current travels along in the space guided by the two copper wires which have approaching infinite ε . To the extent that they are imperfect guides, a small portion of the energy penetrates with very low speed into the copper in a manner identical with the penetration into the high-ε space ahead. A corollary is that as with tubes of magnetic flux, tubes of electric flux do not terminate. They link back with themselves[1].

Theory C.

Theory C asserts that if a battery is connected via two wires to a lamp, there is no electric current in the wires. However, energy current travels from battery to lamp in the dielectric between the wires.

The Battery.

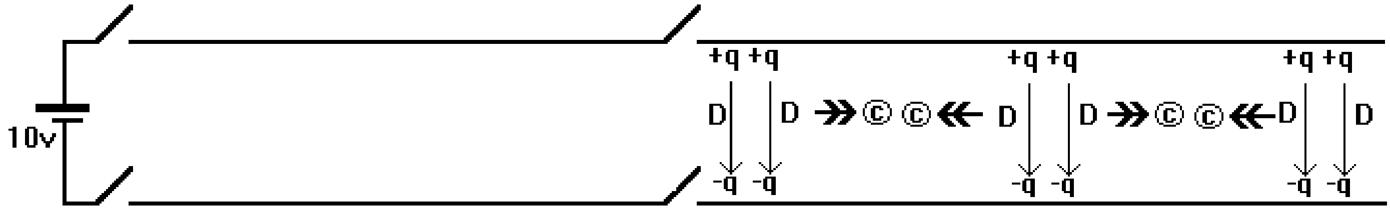


Figure 8

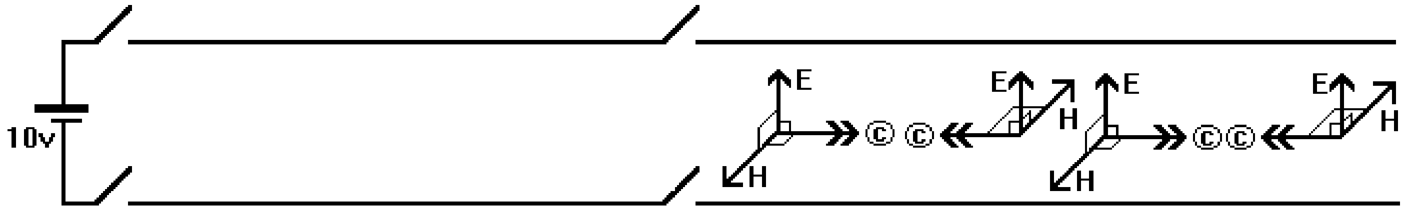


Figure 31

In Fig.8 and Fig.31, the short western space between the battery and near switches 1,2 is in the same state as the eastern space beyond the further pair of switches 3,4, with the same field patterns etc. as drawn.

Necessarily, energy current is vacillating to the east and west in the space between the two conductors in both regions. It reflects westwards at the switches 1,2, and it also reflects eastwards at the western end of the battery plates. In the same way as the capacitors were wrongly drawn in Fig.26 and had to be redrawn correctly in Fig.27 in order to clarify theory, so the battery plates should be redrawn as in Figs. 33,34, to illustrate reality; that the wires are connected to the eastward end of the plates, not to their middle.

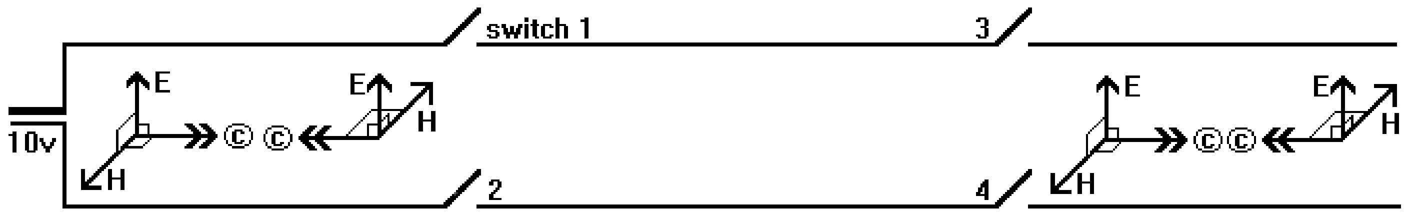


Figure 33

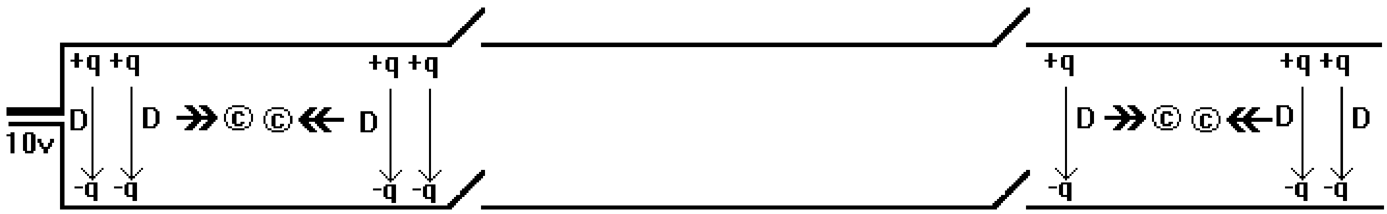
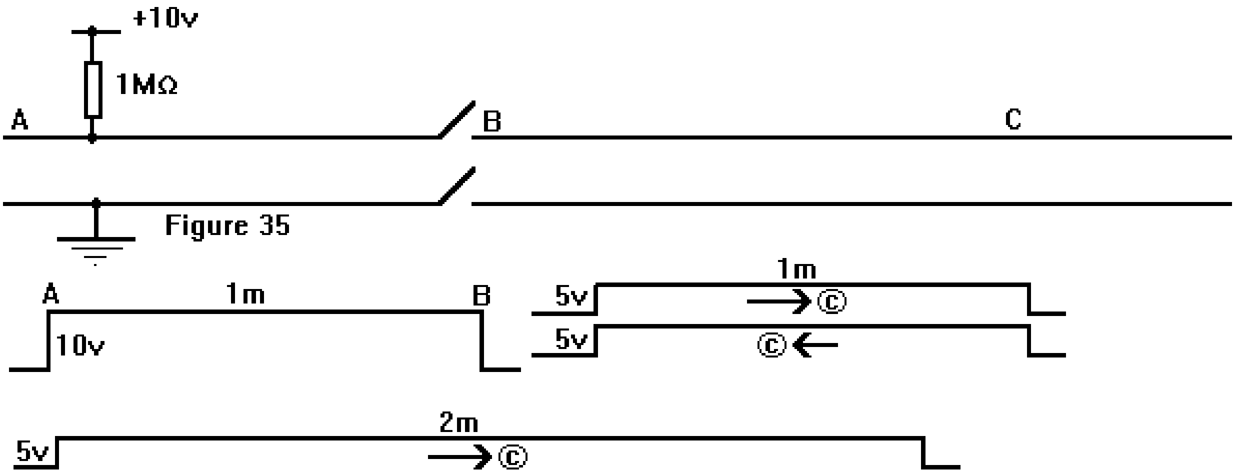


Figure 34

It is then obvious that the battery plates are a western extension of the transmission line comprising the two conductors linking battery to switches 1,2. On closure of switches 1,2, it is this eastwards travelling energy current which rushes forwards, retaining its velocity. There is no change in velocity when the switches are closed. Ions in the battery liquid are not involved, and in any case they travel in the wrong direction, towards the south and north. Chemical reaction in the battery electrolyte replenishes the reciprocating energy current. It is not known whether this energy current is concentrated in the thin interfaces between battery plate and electrolyte, or is broadly spread throughout the electrolyte, or some in each region[2].

The Reed Relay Pulse Generator.



The reed relay pulse generator[3] (Fig.35) was a means of generating a fast pulse using rather primitive methods. A one-metre section of 50 ohm coaxial cable AB was charged up to a steady 10 volts via a one Mohm resistor, then suddenly discharged into a long piece of coax BC by the closure of two switches.

A five-volt pulse two metres wide was found to travel off to the right at the speed of light for the dielectric on closure of the switches, leaving the section AB completely discharged. (The practical device lacked the second, lower switch at B, which is added in the diagram to simplify the argument.)

The curious point is that the width of the pulse travelling off down BC is twice as much as the time delay for the signal between A and B. Also, the voltage is half of what one would expect. It appears that after the switch was closed, some energy current must have started off to the left, away from the now closed switch; bounced off the open circuit at A, and then returned all the way back to the switch at B and beyond.

This paradox, that when the switches are closed, energy current promptly rushes away from the path made available, is understandable if one postulates that a steady charged capacitor is not steady at all; it contains energy current, half of it travelling to the right at the speed of light, and the other half travelling to the left at the speed of light.

Now it becomes obvious that when the switches are closed, the right-wards travelling energy current will exit down BC first, immediately followed by the leftwards travelling energy current after it has bounced off the open circuit at A.

We are driving towards the principle that

Energy (current) E x H cannot stand still; it can only travel at the speed of light.

Any apparently steady field is a combination of two energy currents travelling in opposite directions at the speed of light.

E and H always travel together in fixed proportion Zo.

Electric current does not exist according to Theory C. The so-called electric charge is merely the edge of two reciprocating energy currents.

---

[1]
In fact, tubes of electric flux do not exist on their own. There only exists the TEM wafer composed of a two dimensional surface travelling forward at the speed of light for the medium. One lateral direction is called electric field and the other is called magnetic field. The surface is closed. It is a Gaussian surface. It is like a balloon surface where every point of the surface travels

outwards at the local speed of light. At the rear, the surface speeds backwards towards the battery, the source of the energy. Many of these surfaces co-exist in the space, and periodically divide as changes in impedance are reached. At such points some of the surface retreats and the rest continues forward.
The fancy maths on page 15, while allowing for fields with a forward or backward velocity at the speed of light, clearly disallows stationary fields. If they existed, they should have appeared as further solutions to the equations (2) and (4) on page 15.
The velocity of light for the medium is not the maximum value.
It is the only value.Baby, you're shivering badly in all your parts!

[2]
Nobody will be in the mood to find out for a decade or two. It is all too far removed from the ruling {steady state}conceptual framework of 'ions' slowly drifting in the wrong direction at the wrong speed. Like oil supertankers, research and teaching funding and controlling agencies lack steering power and are slow to change direction. Their contribution to change is to change the names of their courses, but not the content. Researchers into battery and electrolysis do not have the concept of transient behaviour, and will resist it for some further decades.

[3]
Tektronix Pulse Generator type 109. Also see Ref.18

Properties of a Transmission Line, or;

Proof that only one type of wave-front pattern can be propagated down a two-wire system[1].

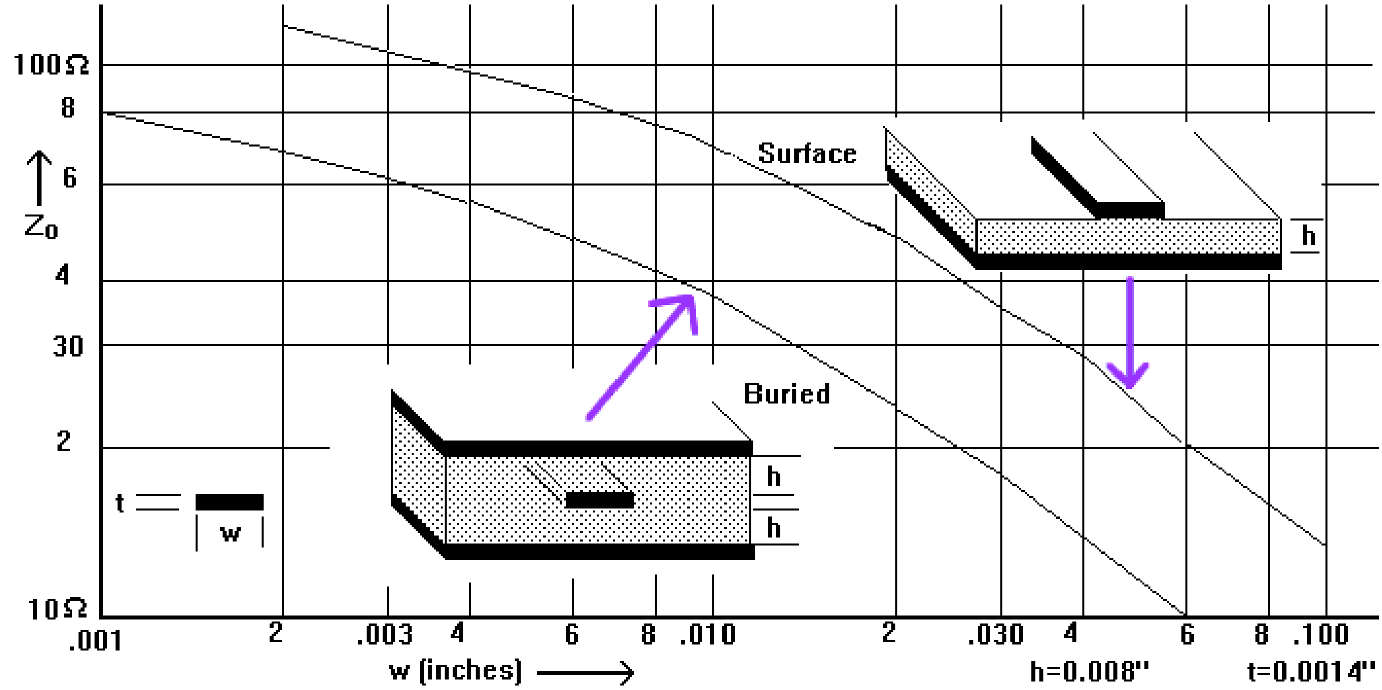


Figure 47 Characteristic Impedance of Surface and Buried Conductors.

In order to discover how we characterise a transmission line we shall consider an observer watching a step passing him along a two-wire line (Fig.36).

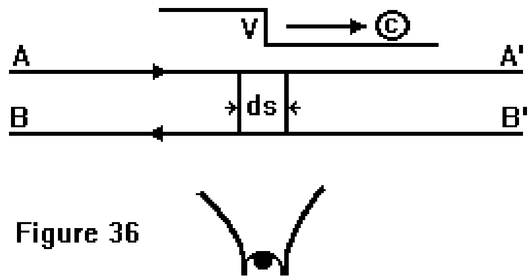


Figure 36

The observer knows (a) Faraday's Law of Induction and (b) that electric charge is conserved.

Use Faraday's law ($V = -\frac{d\phi}{dt}$) around the loop AA'B'B.

Define l as the inductance per unit length of the wire pair, then

$$l = \frac{\phi}{i} \quad (1)$$

In a time δt, the step will advance a distance δs, such that

$$\frac{\delta s}{\delta t} = C \quad (2)$$

and the change of flux will be (from Eqn.1)

$$\delta\phi = l\,\delta s\, i \quad (3)$$

Substitution into (a) Faraday's law gives the input voltage v across AB needed to equal and overcome the back

e.m.f. $v_{back} = \frac{\delta\phi}{\delta t}$.

From (2) and (3),

$$v = v_{back} = l\, i \frac{ds}{dt} = l\, iC \quad (4)$$

Now we consider the conservation of charge. In a capacitor in general, q=cv. In our case, the charge $i\,\delta t$ entering the line in time δt equals the charge trapped in charging up the next segment δs of the line, $c\,\delta s\,v$, where c is the capacitance per unit length between the pair of wires, and $c\,\delta s$ is the capacitance of our section.

$$i\delta t = vc\delta s, \text{ which means that } i = vcC \quad (5)$$

Combining (4) and (5);

$$vi = l\, iC\, vcC$$

$$C = \pm \frac{1}{\sqrt{lc}} \quad [= \pm \frac{1}{\sqrt{(\mu\varepsilon)^2}}] \quad (6)$$

$$\text{and } \frac{v}{i} = Z_0 = \sqrt{\frac{l}{c}} \quad (7)$$

Thus we see that, knowing only Faraday's Law and that charge is conserved, the observer in fig.36 concludes that any step passing him must have a single velocity *C* and a single voltage-current relationship given by an 'Ohm's Law' type relation

$$\frac{v}{i} = Z_0 \quad (8)$$

where Z_0 is a property of (1) f, the geometry of a cross-section of the wires and (2) of μ and ε , characteristics of the medium in which the wires are embedded.

Crosstalk in digital systems, or;

Proof that only two types of wave-front pattern can be propagated down a system of two similar wires and ground plane[2].

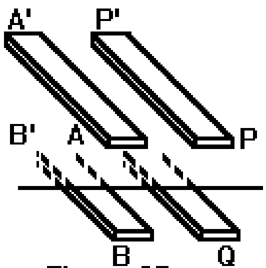


Figure 37

In Fig.37, the method of images is used; it is assumed that $i_b=i_a$, $i_q=i_p$.

The following terms are defined for steady state conditions:

> *l* = Magnetic flux per unit length between AA' and BB' when unit current flows down AA' and back on BB'.

m = Magnetic flux per unit length between AA' and BB' when unit current flows down PP' and back on QQ'.

c = Charge per unit length on AA' and BB' which produces unit voltage drop between AA' and BB'=l/(coefficient of capacitance).

d = Charge per unit length on AA' and BB' which produces unit voltage drop between PP' and QQ'=1/(coefficient of induction).
This could well be called "Mutual Capacitance".

In order to discover how we characterise the four wire system we shall consider an observer watching a step passing him (Fig.38).

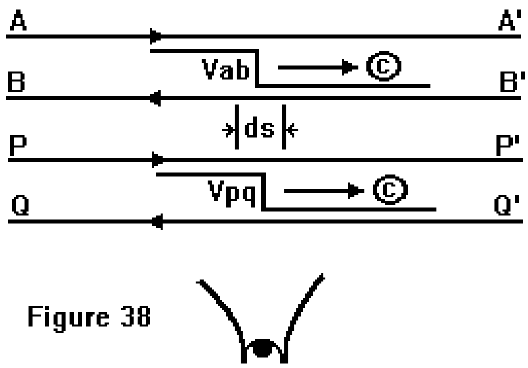


Figure 38

The observer knows (a) Faraday's Law of Induction and (b) that electric charge is conserved.

Now assume that the wave front passing him involves current steps i_a and i_p travelling down the lines with a velocity C.

From $v = \frac{d\phi}{dt}$ between AA' and BB', we get {as in (4)}

$$v_{ab} = l\, i_a C + m\, i_p C \quad (9)$$

Similarly $v = \frac{d\phi}{dt}$ between PP' and QQ', so

$$v_{pq} = l\, i_p C + m\, i_a C \quad (10)$$

Also, from v=q/c {as in (5)},

$$v_{ab} = \frac{i_a}{cC} + \frac{i_p}{dC} \quad (11)$$

$$v_{pq} = \frac{i_p}{cC} + \frac{i_a}{dC} \quad (12)$$

First find C. Eliminate voltages from (9) thru (12).

From (9) and (11) we get

$$l\, i_a C + m\, i_p C = \frac{i_a}{cC} + \frac{i_p}{dC}$$

$$l\, i_a C^2 + m\, i_p C^2 = \frac{i_a}{c} + \frac{i_p}{d}$$

Therefore:

$$\frac{i_a}{i_p} = -\frac{m C^2 - \frac{1}{d}}{l C^2 - \frac{1}{c}} \quad (13)$$

Similarly, from (10) and (12) we get

$$\frac{i_a}{i_p} = -\frac{l C^2 - \frac{1}{c}}{m C^2 - \frac{1}{d}} \quad (14)$$

Eliminate i_a and i_p from (13) and (14) to get

$$C = \pm\sqrt{\frac{\frac{1}{c} + \frac{1}{d}}{l + m}} \text{ or } \pm\sqrt{\frac{\frac{1}{c} - \frac{1}{d}}{l - m}}$$

So in the forward direction there are two possible velocities of propagation,

$$C_e = +\sqrt{\frac{\frac{1}{c} + \frac{1}{d}}{l + m}}$$

or

$$C_0 = +\sqrt{\frac{\frac{1}{c} - \frac{1}{d}}{l - m}}$$

Returning to (13) and using the results for C, we find that the following two wave fronts are possible:

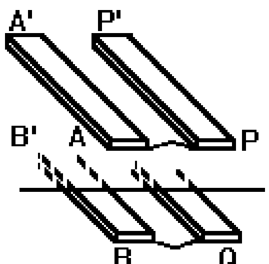


Figure 39

The EM, or Even Mode, wave (Fig.39) is like a TEM step travelling down between two wires made up of A shorted to P and B shorted to Q. It has the higher Z_0 and (in the case of surface, or stripline, conductors) the lower propagation velocity.

$$C_e = +\sqrt{\frac{\frac{1}{c} + \frac{1}{d}}{l + m}}$$

$$Z_{0e} = \sqrt{(l + m)\left(\frac{1}{c} + \frac{1}{d}\right)}$$

$$i_a = i_p$$

$$v_{ab} = v_{pq} \quad (15)$$

2) **OM wave**.

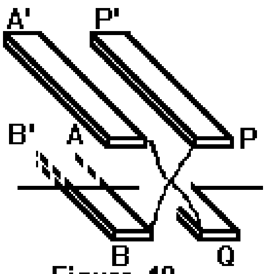


Figure 40

The OM, or Odd Mode, wave (Fig.40) is like a TEM step travelling down between two wires made up of A shorted to Q and P shorted to B.

$$C_0 = +\sqrt{\frac{\frac{1}{c} - \frac{1}{d}}{l - m}}$$

$$Z_{00} = \sqrt{(l - m)\left(\frac{1}{c} - \frac{1}{d}\right)}$$

$$i_a = -i_p$$

$$v_{ab} = -v_{pq} \quad (16)$$

Our initial assumption was that a stable waveform passed the observer; that is, a TEM wave which was in equilibrium[3]. Following that assumption, we concluded from our calculations that no other waveform may pass the observer. However, superposed combinations of EM and OM are permissible, as are seen in photographs in the literature[4]. For instance, a step travelling between AA' and BB' with no voltage visible between P and Q must be a combination of equal amplitudes of EM and OM, which cancel at P (for instance if P has been shorted to ground). As another example, if P is open circuit so that no electric current enters P, then the sum of currents in the EM and OM must be zero. .... [Riposte] .... [Riposte]

---

[1]
Published more thoroughly as Ref.15, Appendix I

[2]
Published more thoroughly as Ref.15, Appendix II

[3]
This observed and photographed phenomenon (see Ref.15, Fig.7 , Ref.3a, Fig.9.4 and Ref.6a, p57) contradicts the starting point of Einstein's theory of relativity. Einstein dismissed such a possibility as absurd (Ref.19, Ref.6a,); ".... If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. [This is what I assume the observer to see, Fig.38.] However, there seems to be no such thing, either on the basis of experience or according to Maxwell's equations."

Notice that in addition to my observing and photographing such a "spatially oscillatory electromagnetic field at rest", my calculations towards the same conclusion are based only on Maxwell's equations. Of course, Einstein never used a high speed sampling oscilloscope. It is less clear why he avoided the imperatives of Maxwell's equations. (However, see Ref.9.)

[4]
Photographs in Ref.15, Fig.7 and Ref.3a, Fig.9.4

Description of crosstalk between parallel buried conductors. (Stripline.)

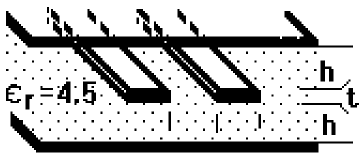


Figure 41

Figure 41 shows a cross section of the lines under discussion.

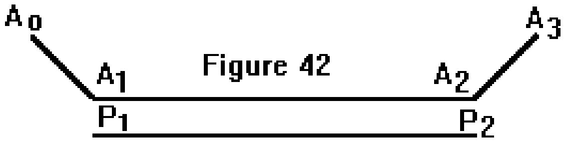


Figure 42

Figure 42 shows a plan view.

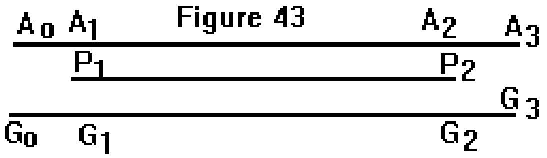


Figure 43

Figure 43 shows a diagrammatic representation of the same.

In a digital system, a voltage-current step v,i, representing a transition from the FALSE state to the TRUE state, is introduced at A_0G_0 .
Lines can be assumed to be lossless and so propagation is TEM.
If Z_0 is the characteristic impedance between the lines A_0A_1 , G_0G_1 , then v= i Z_0 .

When the signal reaches A_1G_1 , the effect of the line P_1P_2 has to be considered.

If the front end P_1G_1 is open circuit, no current can flow in the line, and the only change in Z_0 will be due to the effect of charge moving in a lateral direction across the passive line. This effect may be safely neglected.
If P_1G_1 is shorted, the change in Z_0 on line A which occurs at A_1G_1 is a maximum.
However, if the line spacing is such that maximum crosstalk between lines is acceptably low, this effect may also be neglected.

[If $\frac{\text{maximum crosstalk}}{\text{signal}} = x$,
then maximum change of Z_0 at A_1G_1 is by a factor $\left(1 - x^2\right)$.
In practice, x<0.1. So Z_0 changes by <1%.]

So it may be assumed that the characteristic impedance of a line is not altered significantly by the presence of other lines.

It is not possible for a current voltage signal to travel from A_1G_1 to A_2G_2 and leave the line P_1P_2 unaffected. Two fundamental TEM modes can exist on a pair of parallel conducting strips between parallel ground planes. One mode is called the Even coupled-strip Mode (EM), because the strips are at the same potential and carry equal currents in the same direction. The other mode is called the Odd coupled-strip Mode (OM),

because the strips are at equal but opposite potentials and carry equal currents in opposite directions. $Z_{0e} \rangle Z_0 \rangle Z_{0o}$.

Now the total voltage and current step passing A_1 is v, i, where $\frac{v}{i} = Z_0$.

If P_1G_1 is open circuit, the total current passing P_1 is zero.
So if the voltage-current steps continuing down the line A_1A_2 are respectively v_e, i_e for the EM and v_o, i_o for the OM signal, then

$$i_e = i_0,\ v_e + v_o = v\ .$$

Also,

$$v_e = i_e Z_{0e} \text{ and } v_o = i_o Z_{0o}\ .$$

Since $i_e = i_o$ and $Z_{0e} \rangle Z_{0o}$, then $v_e \rangle v_o$.

So the net voltage appearing on the passive line is positive and equals

$$v_{p_1g_1} = v_e - v_o = i_e Z_{0e} - i_o Z_{0o}\ .$$

The ratio of crosstalk amplitude to signal is

$$\frac{v_{p_1g_1}}{v} = \frac{v_e - v_o}{v_e + v_o} = \frac{i_e Z_{0e} - i_o Z_{0o}}{i_e Z_{0e} + i_o Z_{0o}} = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}\ .$$

So as the signal travels down A_1A_2 , a smaller crosstalk voltage step appears on the line P_1P_2 . The crosstalk that is seen is the small difference between two large signals, whose sum, equal to the original signal v, i, is seen on the driven line A. This crosstalk is here defined as fast Crosstalk (FX), because its full amplitude is reached only if the signal rise time is fast compared to the propagation time down P_1P_2 . The magnitude of the crosstalk so obtained is the maximum that can appear anywhere on the line P, for any values of terminating resistors at P_1G_1 and P_2G_2 . It is a good value to use for worst-case design.

Fast Crosstalk (FX) is a flat topped pulse whose rise and fall times equal t_r for the original signal, and whose width equals twice the propagation time down the passive line.

Slow Crosstalk (SX) is a degenerate case of FX, when the propagation time down the passive line and back is less than t_r . SX has the triangular (noise spike) shape that we are all familiar with in slower logic.

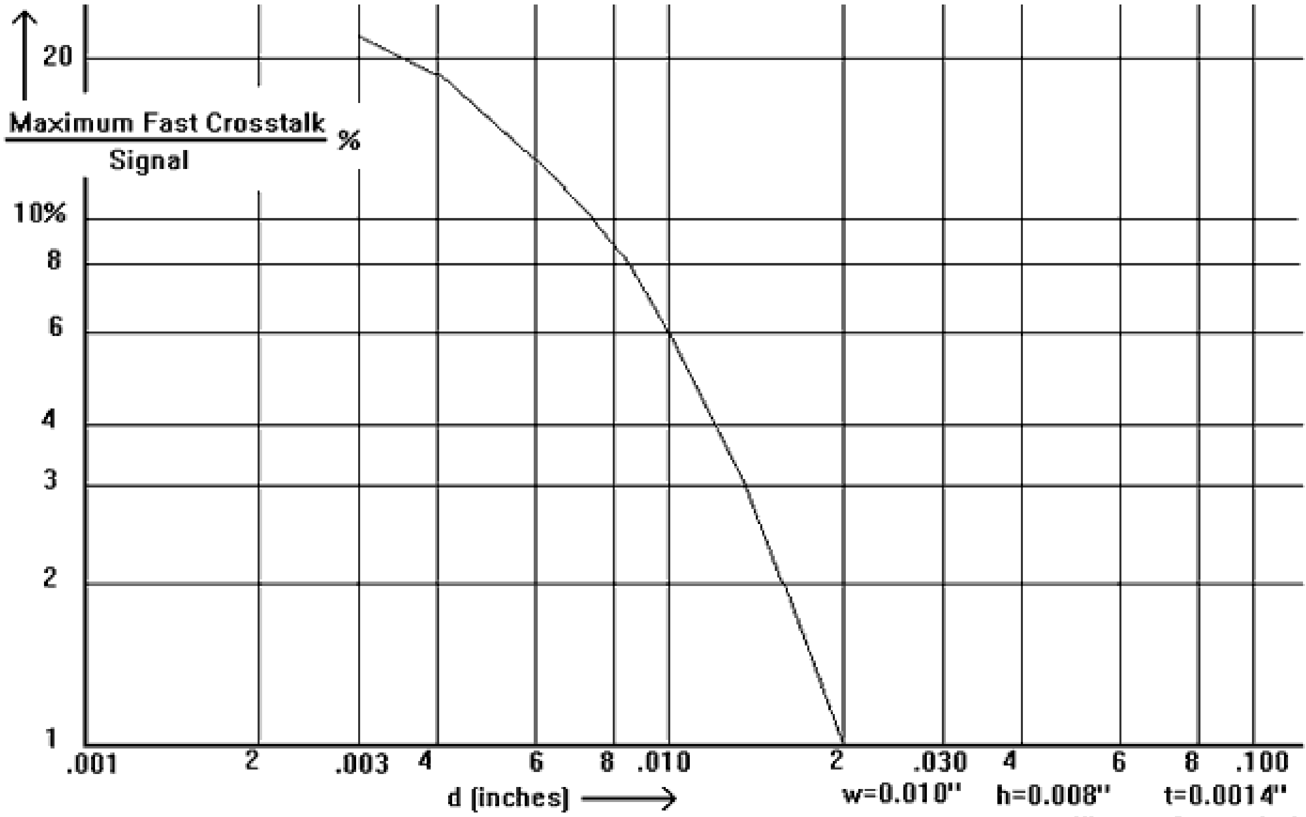


Figure 48 Maximum Fast Crosstalk between Buried Conductors.

Description of crosstalk between parallel surface conductors. (Microstrip.)

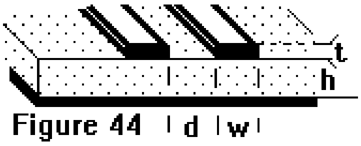


Figure 44 shows a cross section of the lines under discussion.

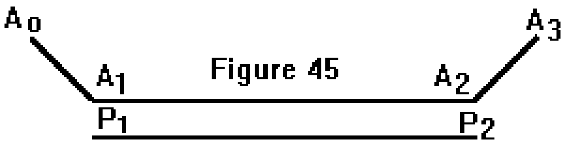


Figure 45 shows a plan view.

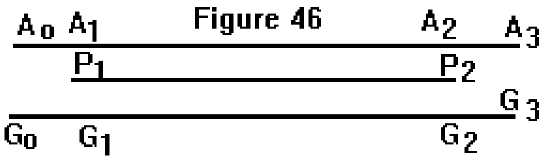


Figure 46 shows a diagrammatic representation of the same.

In a digital system, a voltage-current step v, i, representing a transition from the FALSE state to the TRUE state, is introduced at A_0G_0 .

Propagation is approximately TEM.

If Zo is the characteristic impedance between the lines A_0A_1 , G_0G_1 , then

$$v = iZo.$$

When the signal reaches A_1G_1 , the effect of the line P_1P_2 has to be considered.
It has been shown that the mismatch on line A at A_1 is negligible in practical cases for buried lines.
This is also true for surface lines. So voltage and current v, i, continue along the line A past A_1 .

However, as with buried lines, when the signal v, i, passes A_1 it must break up into a combination of the two possible TEM modes for a pair of parallel conducting strips above a ground plane. These modes are as previously described for buried conductors.

If the front end P_1G_1 is open circuit, it was shown that the ratio of crosstalk amplitude at P_1 to signal is

$$\frac{v_{p_1g_1}}{v} = \frac{v_e - v_0}{v_e + v_0}$$

$$= \frac{i_e Z_{0_e} - i_0 Z_{0_o}}{i_e Z_{0_e} + i_0 Z_{0_o}}$$

$$= \frac{Z_{0_e} - Z_{0_o}}{Z_{0_e} + Z_{0_o}} .$$

So as the signal travels down A_1 A_2, a smaller crosstalk voltage step appears at P_1 . The crosstalk that is seen is the small difference between two large signals, whose sum, equal to the original signal v, i, is seen on the driven line A. This crosstalk is here defined as fast crosstalk (FX), because its full amplitude is reached only if the signal rise time is fast compared to the propagation time down P_1P_2 .

Unlike the case of buried conductors, the magnitude of FX is not the maximum that can appear anywhere on the line P_1P_2 . The reason for this is that as surface conductors are in an inhomogeneous medium, the OM signal travels faster than the EM, and so further down the line P_1P_2 the OM signal appears on its own for a time. This is here defined as Differential Crosstalk (DX) and it greatly exceeds FX. In long lines, it reaches an amplitude of approximately $\frac{v}{2}$, even for widely separated lines.

To reach its maximum amplitude of $\frac{v}{2}$, the difference in propagation times for the two modes down P_1P_2 must exceed the rise time of the original signal v, i.

In practice, this is not the case, and only a fraction of the maximum possible DX appears[1].

The actual amplitude reached by DX at P_2 is equal to

$$\left[\frac{v}{2}\right]\left[\frac{\text{difference in propagation times down } P_1P_2}{\text{signal rise time}}\right].$$

In the case of surface lines, the designer should be sure that FX is not excessive and also that DX is not excessive. Both of these are reduced by increasing line spacing. DX is reduced because there is less difference in propagation times for two modes in more widely spaced lines, as we see in Figure 49 [2].

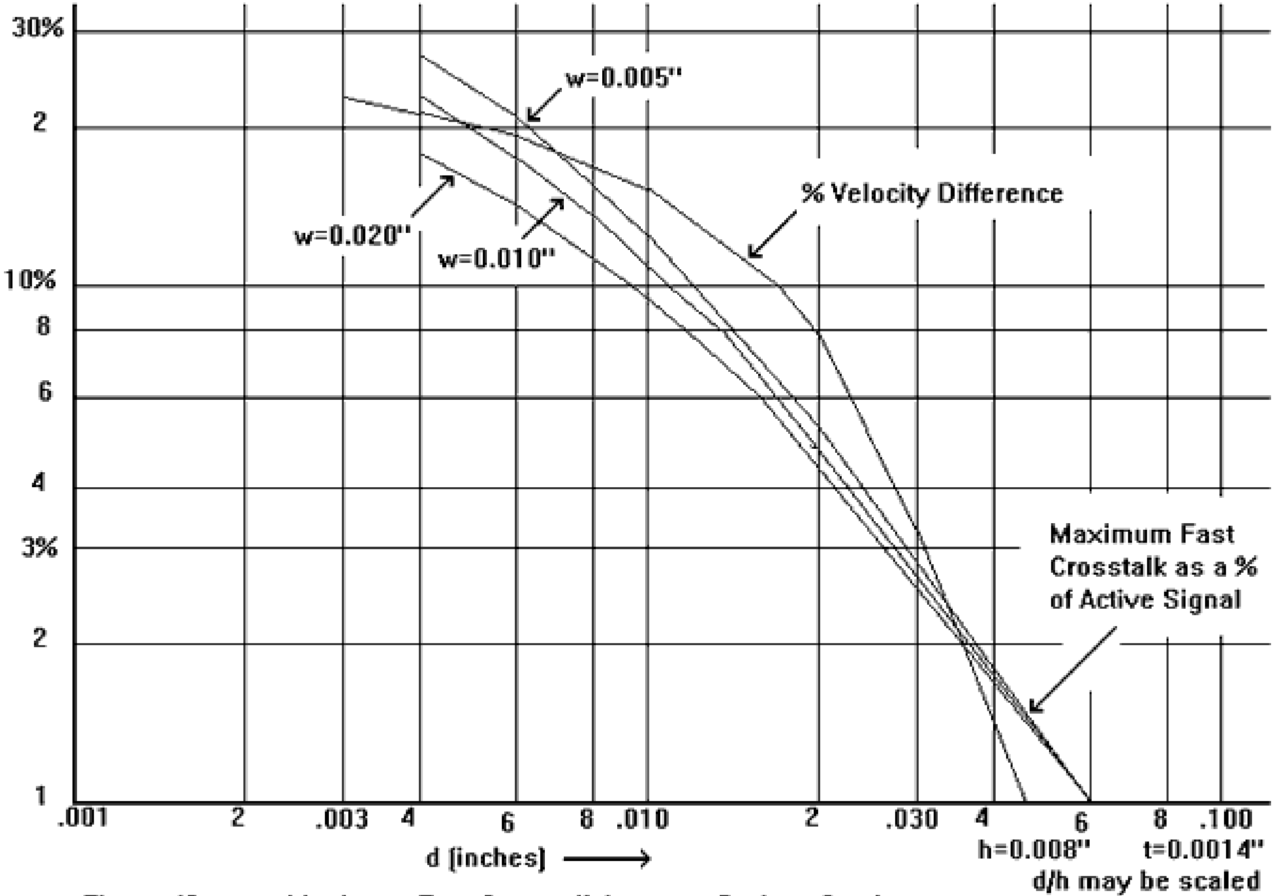


Figure 49 Maximum Fast Crosstalk between Surface Conductors. Percentage Difference in Velocity of the Two Propagation Modes.

If each line is terminated with its characteristic impedance, at A_3G_3 , P_2G_2 , then reflected DX will be less than FX, and so need not be considered. However, if the lines are terminated in a mismatch, such as short circuits or open circuits, then the OM signal, which arrives first at A_2P_2 , will be reflected. On its way back to A_1P_1 , it will draw further away from the (now reflected) EM signal. So if the lines are badly terminated, the amplitude reached by the *reflected* DX when it reaches P_1 will equal

$$\left[\frac{V}{2}\right]\left[\frac{\text{difference in propagation times down } P_1P_2 \text{ and back}}{\text{signal rise time}}\right]$$

This is double the amplitude reached by DX. However, this is not a practical case, because for reasons of reflections alone not related to crosstalk, A_2P_2 must be terminated properly[3].
So we need only consider the case when A_2G_2 is terminated properly, either by a further length of line A_2A_3 or by a resistor Zo, and there is only a mismatch (short or open) at P_2G_2 .
In that case, the incident OM signal will be reflected in two modes, half OM and half EM, and it can be shown that the maximum amplitude of *reflected* DX will be only about half the maximum DX.

The conclusion is that in practice the problem of *reflected* DX may be ignored, and one need only consider FX and DX.

The passive line may have two active lines, one on each side of it, so the figure for crosstalk in Figures 48 (graph for stripline crosstalk) and Figure 49 (graph for microstrip crosstalk), should be doubled for worst case design. If P_1 is terminated with a resistor equal to Zo, the crosstalk is halved. However, it is safer to ignore this.

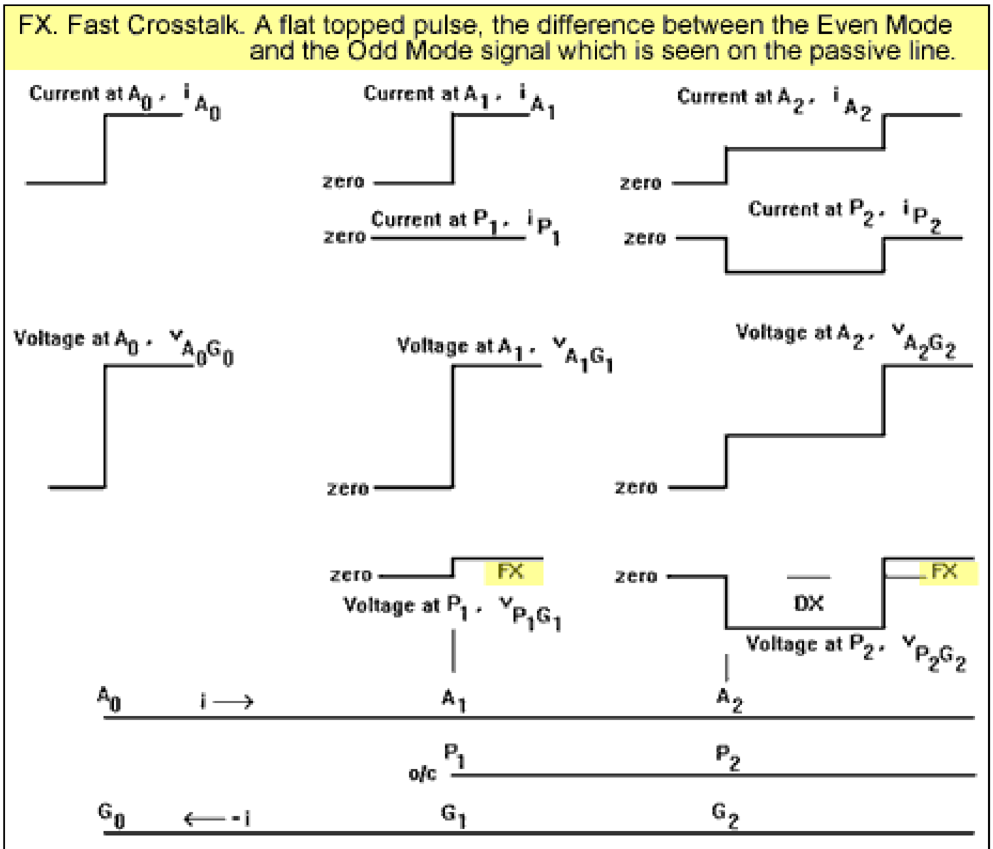


Figure 50. Signal waveforms at various points down the active and passive lines.

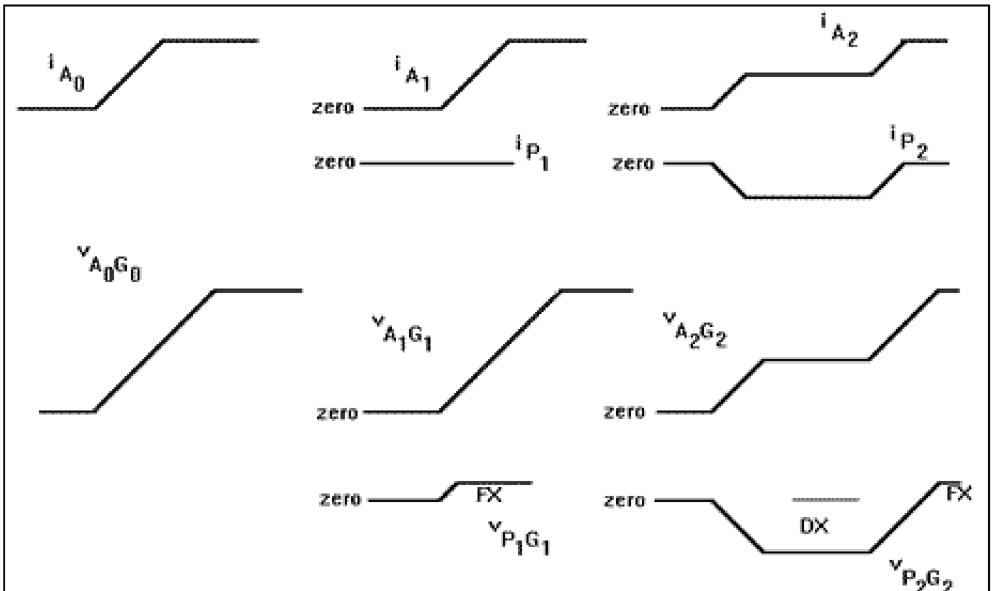


Figure 51. The same situation as Figure 50, but with finite rise time signal.

Note: The [classic oscilloscope photographs](http://www.ivorcatt.com/emcrosstalk.htm) *of these waveforms* taken during the crucial experiment in the 1960s are at http://www.ivorcatt.com/emcrosstalk.htm.

---

[1]
All of this theory applies to buried lines and surface lines in a printed circuit board. However, it also applies to a cableform with two twisted pairs or with two signal lines and one return (ground) line. In the case of a cableform, the theory indicates various important things. (1) FX reaches an easily calculable maximum regardless of length of cable, which is good. (2) DX reaches half the logic signal, which is disastrous. Therefore the dielectric must be consistent, and not a mixture of air and teflon, so that DX disappears.

[2]
Velocity difference is caused by the EM field being concentrated less in (faster) air than the OM signal, so that EM arrives downstream later than OM. However, the two field patterns are more similar to each other with widely spaced lines, so the

velocities are more similar, approximating towards the velocity for a single line on its own. (This last point is proved in ref. 15, Fig.39.)

[3]
This is not always true. "Series termination" of logic signal lines is a counter-example. A high speed logic gate might have a 47 ohm series resistor on its output into a 50 ohm line which is open circuit at destination. This system is used to minimise power dissipation, but happens to increase the effect of DX.

Printed circuit boards for high speed logic.

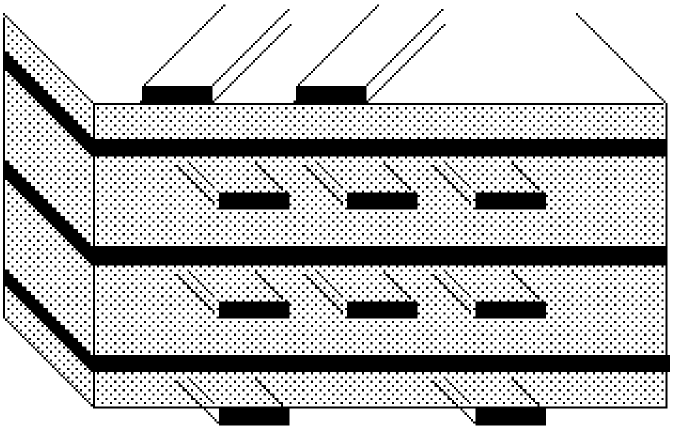


Figure 52. PCB for high speed logic.

High speed (1 nsec.) logic systems require voltage planes to separate successive layers of signal lines (Fig.52) in order to keep signal cross coupling (noise) down to a reasonable level (say 10% of signal amplitude).At a frequency of 1 GHz, skin depth in copper is 2.10^{-4} cm. (=0.00008 in.) (Ref.20). At 10 GHz, skin depth drops to 7.10^{-5} cm. (=0.00003 in.).The thinnest practicable laminated copper is about 0.001 in., which is more than ten times the skin depth. This means that in practice, a signal travelling down a signal line and returning by the immediately adjacent voltage plane(s) will not penetrate beyond the plane(s), and each voltage plane will screen signals above it from signals below it with negligible crosstalk through voltage plane. So long as a signal is transmitted down between a signal line and the voltage plane(s) immediately above and/or below it, the only crosstalk (noise) of significance will be between (adjacent) signal lines in the same plane[1]. Care must be taken that at its source and destination, the signal is referenced to the correct voltage plane(s), and this will now be discussed.

Calculation.

As a practical example, consider (Fig.49) a surface passive line with potentially active lines on each side of it, with w=0.010" and d=0.010".

FX from one adjacent line is 11%, so from the two active lines it is 22%. This is rather high unless the lines are short. We might therefore reduce h by $\frac{3}{4}$ from 0.008" to 0.006". The effect is about the same as increasing d by $\frac{4}{3}$ to 0.013", which reduces FX to an acceptable 8%, or 16% for the two active lines[2].

DX is given in one curve only in Figure 49, and this curve relates to w=0.010". With w=0.010" and d=0.010" the velocity difference F is 15%, or 0.15. It can be shown that as a % of the active signal,

$$DX = \frac{F.L_p}{2C_{eg}t_r}$$

where F is the % velocity difference,

Assume; the length of the passive line $L_p = 12"$; the velocity of propagation $C_{eg} = 6"$ per nsec in an epoxy-glass PCB; and the active signal rise time $t_r = 2\text{nsec.}$ For w=0.010" and d=0.010, Figure 49 shows that

F=15%, or 0.15 . Thus, $DX = \frac{(0.15).12}{2(6.10^{9})(2.10^{-9})} = 7.5\%$

Decoupling by Voltage Planes.

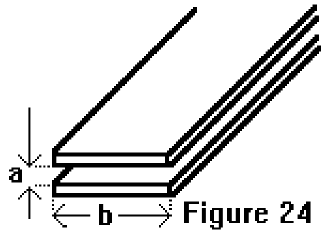
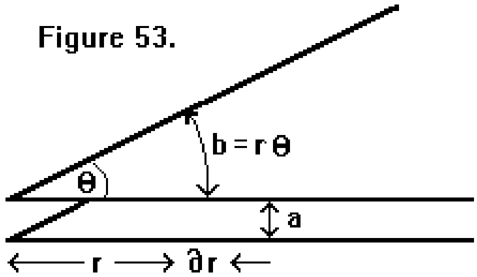


Figure 24

In order to understand the nature of the decoupling action at a point between parallel voltage planes, first consider the parallel-plate transmission line (Fig.24), which has a $Z_0 = \frac{a}{b}\sqrt{\frac{\mu}{\varepsilon}}$. This formula still applies for each small section of a transmission line where the width a is varying, for example for a wedge-shaped line (Fig.53.).

Figure 53.



Over a distance δr the above formula becomes

$$Z_0 = \frac{a}{r\theta}\sqrt{\frac{\mu}{\varepsilon}} .$$

Now if $\theta = 2\pi r$, we are considering a complete plane. The signal travels out radially between the planes (Ref.21), and we get

$$Z_0 = \frac{a}{2\pi r}\sqrt{\frac{\mu}{\varepsilon}} .$$

Now we know that, in a medium of permittivity e and permeability m, the outwards velocity of the signal through the epoxy-glass dielectric is

$$C_{eg} = \sqrt{\frac{1}{\mu\varepsilon}} .$$

Therefore

$$C_{eg} = \frac{r}{t} = \frac{1}{\sqrt{\mu\varepsilon}} ,$$

where t is the time since the signal was introduced at the centre.
So using this last equation for the distance r we get

$$Z_0 = \frac{a\mu}{2\pi t}\ \Omega$$

where a is in metres.

A reflection related to Z_0 arrives back at the centre at time 2t. If Z_0 is small when $2t = t_r$, (the risetime of the output of the logic gate,) then natural decoupling between planes is satisfactory.

Calculation.

As a practical example, if 2t=1ns, d=0.5mm., $\mu = 4\pi.10^{-7}$, then

$$Z_0 = \frac{\frac{1}{2}\ .\ 10^{-3}\ .\ 4\pi\ .\ 10^{-7}}{2\pi.\ \frac{1}{2}\ .\ 10^{-9}} = 0.2\ \Omega$$

This calculation shows that natural decoupling between voltage planes is satisfactory for a single switching load of high speed logic, or for a number of loads in the same integrated circuit[3]. We then prevent superposition of the current transients into a number of integrated circuits switching at the same instant from generating unacceptably large voltage transients between planes by adding extra discrete ($1\mu F$) decoupling capacitors distributed at intervals of a few centimetres. The proportion of the surface area occupied by the miniature tantalum capacitors will be insignificant.

---

[1]

One argument which can be used to dismiss the feared additional effect of a further active line next to the nearest active line is as follows. In Figure 49, if line width w and line spacing d are both 0.010", then maximum FX is 11%. However, the next parallel active line is at a spacing d of 0.030", causing it to add a negligible further FX of 2.5%. The reality, of course, is that the nearer active line shields the further active line from the passive line.

[2]

There is, however, a price to be paid for reducing h by 3/4 to 0.006" (equivalent to w=0.013", h=0.008"), because, see Figure 47, Zo drops from 74 ohms to 64 ohms. As a result, it takes more current to drive the line, slowing down driving circuit and increasing power dissipation. Generally, reducing crosstalk by hiding lines close to planes (a) reduces (impedance and therefore) speed and (b) increases power dissipation.

[3]

perhaps switching a transient 100ma or 500mw. Think of a 5v power supply with source impedance of 0.2 ohms driving a 50 ohm load, resulting in a drop of (0.2/50.2)..5v=20mv across the source and a drop of the effective supply from 5v to 4.98v.

The L-C Oscillator Circuit.

When a charged capacitor is connected to an inductor, the conventional analysis is to equate the voltage across the capacitor with the voltage across the inductor

$$v = \frac{1}{C}\int i\,dt = -L\frac{di}{dt}\ .$$

Differentiating, we get

$$\frac{d^2i}{dt^2} = -\frac{i}{LC}$$

This is then recognised as having as a solution simple harmonic motion (SHM),

$$v = v_0 \sin\varpi t\ ,$$

where

$$\varpi^2 = \frac{1}{LC}\ .$$

The traditional analysis assumes that when current is switched into the inductor, it appears instantaneously at all points in the inductor; the use of the single, lumped quantity L implies this. Similarly, it is assumed that the electric charge density at all points in the capacitor is the same[1]; that there are no transient effects such that the charge density is greater in certain regions of the capacitor plates.

Work on high-speed logic systems led to a reappraisal of the conventional analysis, particularly insofar as it bears on the choice of type and value of decoupling capacitor for logic power supplies.

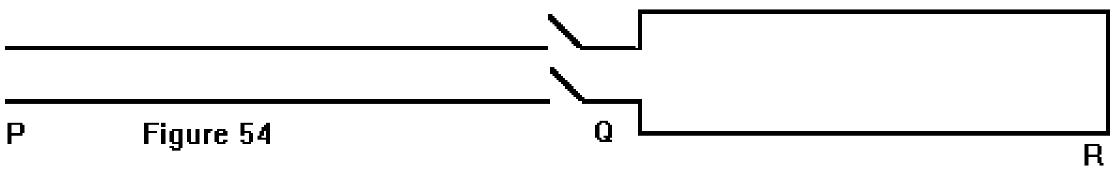


Figure 54

In Figure 54, consider a capacitor (or open-circuit transmission line) which is connected to a single-turn inductor (or short-circuited transmission line). The initial state is that the capacitor was charged to a voltage v and then connected to the inductor by closing the switches.

Figure 55 shows the coefficients which apply when signals reflect or pass through discontinuities in the circuit.

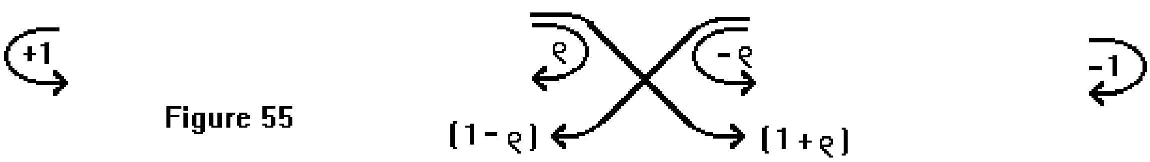


Figure 55

If at a certain time the signal in the capacitor PQ has an amplitude v_{x-1} and the signal in the inductor QR is y, then the sequence in Figure 56 will occur.

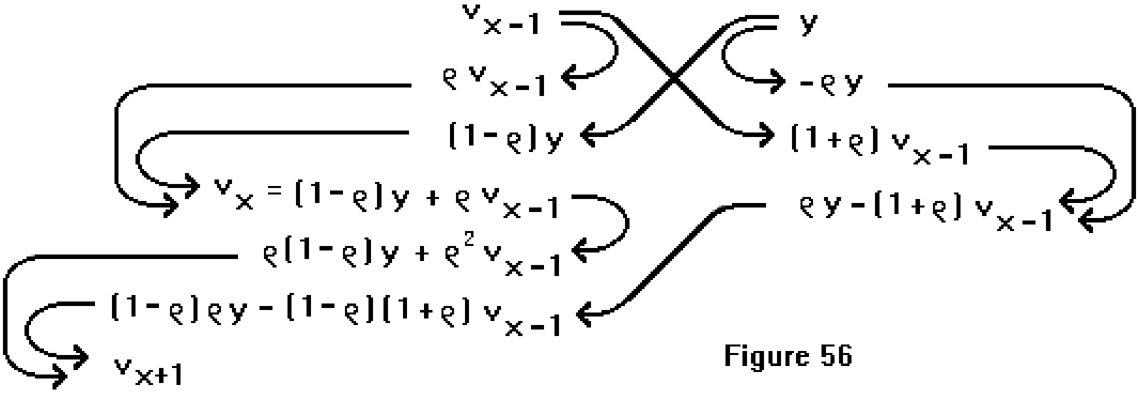


Figure 56

v_{x-1}, coming from the left to Q, breaks up into a reflected signal

$$\rho v_{x-1}$$

and a forward signal

$$(1+\rho)v_{x-1}$$

because the two relevant coefficients are ρ and $(1+\rho)$. At the same time, the signal y, coming from the right towards Q, breaks up into a forward going $(1-\rho)y$ and a reflecting $-\rho y$, because the relevant coefficients are $(1-\rho)$ and $(-\rho)$. $(1-\rho)y$, travelling to the left from Q, combines with the leftwards travelling ρv_{x-1}. When they reach the open circuit at P, where the reflection coefficient is +1, they reflect back towards Q. The value of this signal is now v_x, the next in the sequence, and we have calculated it to equal $(1-\rho)y + \rho v_{x-1}$. Similar arguments explain all other amplitudes in the sequence.

The bottom line in the sequence gives us the value of v_{x+1} in terms of y and v_{x-1}.
If we add v_{x-1} to this value of v_{x+1}, we get

$$v_{x+1} + v_{x-1}$$

$$= 2\rho(1-\rho)y + \left[1 - (1-\rho^2) + \rho^2\right]v_{x-1}.$$

$$= 2\rho(1-\rho)y + 2\rho^2 v_{x-1}$$

$$= 2\rho\left[(1-\rho)y + \rho v_{x-1}\right].$$

But the middle of the sequence tells us that

$$v_x = (1-\rho)y + \rho\, v_{x-1}.$$

Therefore,

$$v_x = \frac{v_{x+1} + v_{x-1}}{2\rho}.$$

$2v_x, 2v_{x+1}, 2v_{x+2}$, etc., is a sequence of amplitudes seen in the capacitor, and they obey the above formula. Now since

$$\sin\alpha = \frac{\sin(\alpha+\delta\alpha) + \sin(\alpha - \delta\alpha)}{2\cos\delta\alpha}$$

we can see that one possibility is that the sequence in v_x represents a series of steps which approximate to a sine wave.

The conclusion is that one waveform which can be supported by an L - C circuit is a sine wave, where the C is an open-circuit transmission line and the L is a short-circuited transmission line. The larger the value of ρ [2], the smaller is the forward flow of current each time across the central node at Q between the C and the L. This means that there is more time between maxima in the voltage level in C, and a lower "resonant frequency"[3].

---

[1]
Bleaney B.I. and Bleaney, Electricity and magnetism, 2nd Edn., pub. Oxford, Clarendon, 1965, p258.
Fewkes J.H. and Yarwood, Electricity and Magnetism vol.1, pub. University Tutorial Press, London, 1956, p505.

[2]
i.e., the bigger the discrepancy between Z_{0_C} and Z_{0_L}, or to put it another way, the more capacitive the capacitor and/or the more inductive the inductor,

[3]
First published in Proc IEEE, vol 71, No. 6, June 1983, p772.

Further discussion

The Inductor as a Transmission Line.

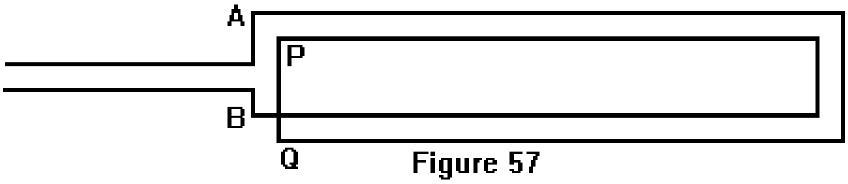


Figure 57

The inductor is a time-delay and energy trap. A voltage step enters and travels back and forth through the device, with gradual trapping of energy inside. The time taken for the energy leaving the inductor to rise to equal the amount entering is dependent on the mismatch between the characteristic impedances and also the time delay involved in traversing the device. If the mismatch is great, less energy enters or leaves per round trip, so the time taken for the equality of energies is longer and therefore the inductance is greater.

The single turn inductor is a transmission line with an increase in characteristic impedance followed by a short circuit, discussed in the previous chapter. Here we discuss the two-turn inductor.

When a wavefront travelling down an infinitely long cable reaches AB, it breaks up into three parts; a reflection v_{RC} back up the cable, and two transmitted parts. The transmitted parts are the even and odd modes of propagation discussed in the earlier chapter on crosstalk. The voltages and currents on the lines AB and PQ are

$$v_{ab} = v_e + v_0 \quad (1)$$

$$i_{ab} = i_e + i_0 \quad (2)$$

$$v_{pq} = v_e - v_0 \quad (3)$$

$$i_{pq} = i_e - i_0 \quad (4)$$

The line PQ has a short which clamps its voltage to zero.

$$v_{pq} = 0 \quad (5)$$

$$\therefore v_e = v_0 \quad (6)$$

Using basic transmission line theory, (1)-(4) can be solved, yielding

$$T_{ce} = \frac{2}{2 + R_e + R_o} \quad (7)$$

$$T_{co} = \frac{2}{2 + R_e + R_o} \quad (8)$$

$$R_c = \frac{2 - R_e - R_o}{2 + R_e + R_o} \quad (9)$$

Where

$$R_e = \frac{Z_{cable}}{Z_{even}}$$

$$R_o = \frac{Z_{cable}}{Z_{odd}}.$$

T_{ce} means the transmitted voltage from the cable to even mode and R_c is the reflected part from the junction back into the cable. By repeating terminal conditions for the inductor to cable direction, we get

$$T_{ec} = \frac{4R_e}{2 + R_e + R_o} \quad (10)$$

$$T_{oc} = \frac{4R_o}{2 + R_e + R_o} \quad (11)$$

$$R_{eo} = \frac{2R_e}{2 + R_e + R_o} \quad (12)$$

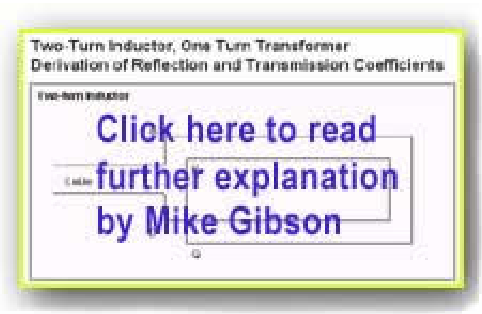
$$R_{ee} = \frac{-2 + R_e - R_o}{2 + R_e + R_o} \quad (13)$$

$$R_{oo} = \frac{-2 - R_e + R_o}{2 + R_e + R_o} \quad (14)$$

$$R_{oe} = \frac{2R_o}{2 + R_e + R_o} \quad (15)$$

The far end of the inductor requires special attention which eliminates some mathematics. Understanding the meaning of even- and odd-mode propagation, one can see that the odd-mode is terminated by an open circuit and the even mode by a short-circuit. Since the incident voltages are already in the correct modes and each mode is individually terminated, there will be no transfer between even and odd mode at the far end of the inductor. The odd mode is reflected positively and the even mode is simply inverted.

A computer iteration of the two-turn inductor was written by Michael S. Gibson, and the results confirmed that the two-turn inductor had the expected exponential waveform with four times the time constant for the one-turn inductor. However, the waveform only approximates to an exponential, but is made up of a series of small steps. The waveforms were published in Proc. IEEE[1]



Mike Gibson and Ivor Catt also worked on **The Transformer as a Transmission Line.**

Mike Gibson's computer Simulation of Inductor and Transformer as transmission line

The time constant, the time for the voltage in the inductor to fall to e^{-1} of maximum, is $\tau = \frac{L}{R}$, where R is the characteristic impedance of the cable Z_c. N is the number of iterations of the program, or traverses of the inductor, needed to reach τ. So the inductance is $L = NTZ_c$, where T is the time taken to traverse the inductor once.

The quadrupling of the inductance from a one-turn inductor results from the difference in the characteristic impedance of the even and odd modes. At low mismatches of even and odd mode (when they are approximately equal), the inductance is only twice that of a one-turn inductor of the same length since the lines are uncoupled (and "crosstalk" is minimal). In this case, the two-turn inductor behaves like a single turn of twice the length. But at high mismatches between even and odd modes, that is, when the lines AB and PQ are close together, the lines are tightly coupled and the modes are trapped. This trapping of the modes increases the time taken to reach the steady state (a short circuit), and is detected as an increase in inductance.

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[1]
First published in Proc IEEE, vol 75, No. 6, June 1987, p849.

Calculation of Formulae.

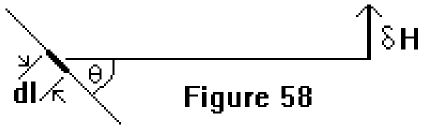

Figure 58

Oersted discovered that a compass needle was deflected by a nearby electric current. This was quantified in the Biot-Savart Law, which says that if a small length δl of conductor carries current i,

then the magnetic field strength at distance r and angle θ is

$$\delta H = \frac{i \delta l \sin\theta}{4\pi r^2}.$$

(The $\sin\theta$ merely indicates that if the electric current is not in an optimum direction, then the field at that point is diminished.) This is restated as Ampere's Rule; $\int H dl = i$. This says in general that the line integral of the magnetic field in a closed loop equals the electric current passing through the loop[1]. In particular, the magnetic field strength H in a circular path of radius r surrounding an electric current i at the centre is

$$H.2\pi r = i, \text{ or } B = \frac{\mu i}{2\pi r}.$$

Magnetic field surrounding current in a single long conductor.

Self inductance of a long straight conductor.

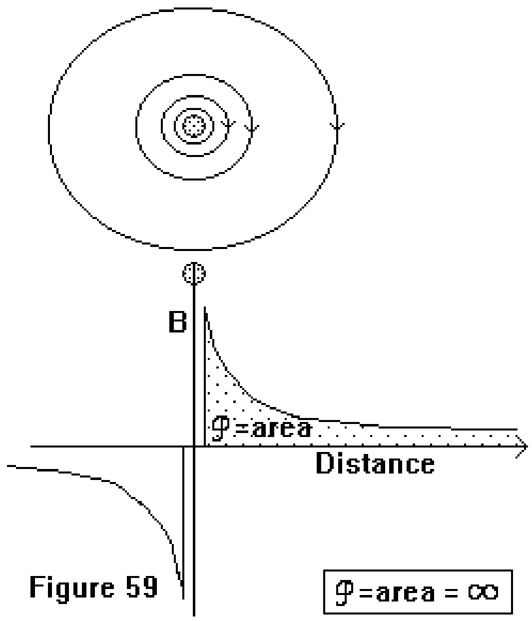

Figure 59

At distance r out from the conductor,

$$B = \frac{\mu i}{2\pi\, r}.$$

Integrate the total magnetic flux from the edge of the conductor out to infinity.

$$\phi = \int B dr$$

$$= \frac{\mu i}{2\pi} \int_r^\infty \frac{dr}{r}$$

$$= \frac{\mu i}{2\pi} \left[\log \infty - \log r\right] = \infty \cdot$$

The self inductance per unit length is

$$L = \frac{\phi}{i} = \infty.$$

The self inductance of a long straight conductor is infinite.

This is a recurrence of Kirchhoff's First Law, that electric current cannot be sent from A to B. It can only be sent from A to B and back to A.

Self Inductance of a Pair of Parallel Conductors.

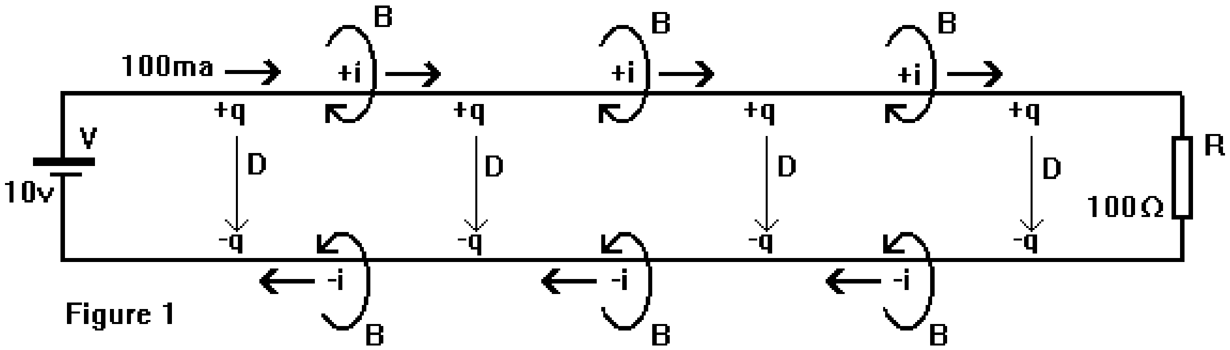

Figure 1

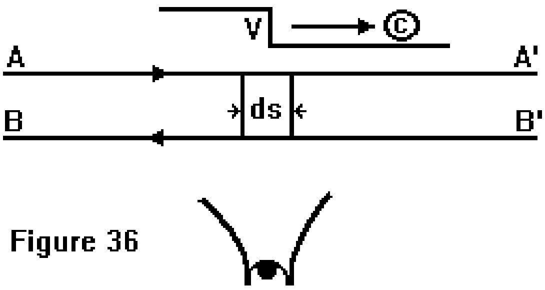

Figure 36

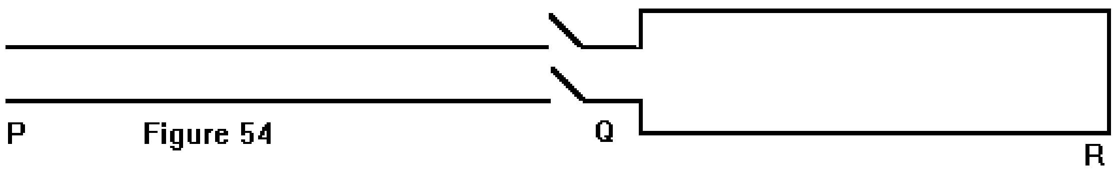

Figure 54

In Figures 1,36,54, the magnetic flux created by the forward current in the first wire is partially cancelled by the magnetic flux created by the current flowing in the opposite direction in the other wire. The result is a finite total flux and finite self inductance. To calculate this $l = \frac{\phi}{i}$ per unit length, we integrate the magnetic flux passing between the two wires. We integrate from r to a, the distance between wire centres[2].

$$\phi = \int B dr$$

$$= \frac{\mu i}{2\pi} \int_r^a \frac{dr}{r}$$

$$= \frac{\mu i}{2\pi}\left(\log a - \log r\right)$$

$$= \frac{\mu i}{2\pi}\log\frac{a}{r}$$

This is the magnetic flux that one wire contributes. The total flux is twice this.

Therefore the self inductance per unit length (equal to $\frac{\phi}{i}$) is

$$2l = \frac{\mu}{\pi}\log\frac{a}{r}$$

Mutual Inductance between Two Pairs of Parallel Conductors.

The calculation is similar to before, except that the integration must be from the first conductor to the second conductor, that is, from b (=BP) to a (=BQ), for the effect of the nearer wire B. (b, a, follow the terminology in Table 1(g), p24. BP, BQ are in Fig.61.) Then we integrate similarly for the further wire A, between distances d (=AP) and c (=AQ). Subtract the two results, because, as we can see, the two fluxes are in opposite directions.

$$M = \frac{\mu}{2\pi}\log\frac{a}{b} - \frac{\mu}{2\pi}\log\frac{c}{d}$$

$$\therefore\ M = \frac{\mu}{2\pi}\log\frac{ad}{bc}.$$

This is a general formula which remains true for any arrangement of two pairs of parallel wires (which do not have to lie in one plane). The practical case is more orderly. For instance, each pair might be similar. In that case, when the wires lie in one plane and the mean distance between pairs(=AP) is r times the separation(AB) of a pair, and AP>>AB, the formula can be shown to reduce to

$$M = \frac{\mu}{2\pi}\log\left(1+r^2\right)\cdot$$

The mutual inductance is reversed if PQ is to the left of AB instead of to the right. However, the practical case for crosstalk in a printed circuit board is where the four similar wires (or actually, two wires plus their reflection in a ground plane) form a rectangle instead lying in one plane. In this case, using the symbols in Table 1(f), p24,

$$M - \frac{\mu}{2\pi}\log\frac{a^2+d^2}{d^2}\cdot$$

In order to compare with the graphs for crosstalk in a PCB on p17, 18, we also need L_e , the self inductance for the even mode, and L_o , the self inductance for the odd mode. L_e is the flux which links a pair of wires AB as a result of current, half of it down A and back on B, and the other half down P and back on Q. This equals

$$\frac{L}{2}+\frac{M}{2}.$$

[The best formula to use for L in this context is

$$L = \frac{\mu}{2\pi} \log \frac{a^2}{r^2}$$

to make L and M look similar, rather than (p24) $\frac{\mu}{\pi} \log \frac{a}{r}$ as shown against Table 1(c).]

---

[1]This is Faraday's discovery of electromagnetic induction. Changing magnetic flux through an area creates an electric voltage which tends to drive electric current around the perimeter in a direction opposing the change of flux. (The opposition is contained in Lenz's Law.)

[2] W H Hayt, Engineering Electromagnetics, McGraw-Hill 1958,1989, p390/391, S. Ramo and others create a can of worms by not taking the centre of the two wires. Candidates are the near edge or the top point of one of the wires. I think this last choice leads them to end up with cosh rather than log, and create havoc in their wake. Since none of the choices is absolutely true, it is important and permissible to choose an approximation which leads to the mose elegant, malleable and consistent set of equations. Experience shows that the proper choice is the centre of each of the wires. Absolute truth for the formula is approached for perfect conductors if the radius of the wires is insignificanct compared with their separation.

Crosstalk between Two Pairs of Parallel Conductors.

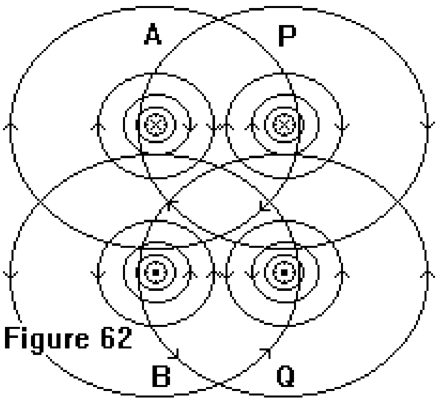

Figure 62

Our approach is the same as with crosstalk in a printed circuit board, see Description of crosstalk between parallel buried conductors et seqq.

We realise that the self inductance of two identical inductors in parallel is half that of one inductor. Thus, if the two pairs of lines are widely spaced so that M is negligible, then

$$L_e = \frac{L}{2}.$$

The capacitance of two capacitors in parallel is double that of one capacitor. The characteristic impedance of two transmission lines in parallel is half that of one on its own. Thus, L_e, L_o, Z_{0e}, Z_{0o} are based around $\frac{L}{2}$ and $\frac{Z_0}{2}$, where L and Zo are the values for one isolated pair of wires AB[1].

Inductance is defined as the amount of magnetic flux which threads a circuit when unit electric current flows through the circuit. Now if unit electric current flows in the Even Mode (Fig.62), that is, down lines A and P and back on lines B and Q, then only half of the current flows in an individual line A. This causes magnetic flux of quantity L/2 to thread circuit AA'B'B, and magnetic flux of quanitity M/2 to thread circuit PP'Q'Q. The other half current, flowing down PP' and back on QQ', causes magnetic flux of quantity M/2 to thread circuit AA'B'B. This argument shows that

$$L_e = \frac{L+M}{2} = \mu f_e,$$

where f_e is the function of the geometry of the cross section of the conductors (see The analogy between L, C and R). Similarly,

$$L_o = \frac{L-M}{2} = \mu f_o.$$

Our argument about f leads us to conclude that

$$C_e = \frac{\varepsilon}{f_e} \text{ and } Z_{0e} = f_e\sqrt{\frac{\mu}{\varepsilon}}.$$

And so on.

From the previous sections , $L = \frac{\mu}{\pi} \log \frac{a}{r}$ and $M = \frac{\mu}{2\pi} \log \frac{ad}{bc}$.

$$L + M = \frac{\mu}{2\pi} \log \frac{a^2}{r^2} + \frac{\mu}{2\pi} \log \frac{a^2 + d^2}{d^2} .$$

In Figure 62, AP=d and PQ=a. L_e ranges from L/2 for lines widely separated (becoming the L of two independent inductors in parallel) to L for lines which are very close such that M approaches L in value[2]; coupling approaches unity. Generally, therefore,

$$L_e = \frac{L + M}{2} .$$

Also from first principles, L, the flux generated in AB by current in AB results from integrating from r to a, while M, the flux generated in AB by current in PQ results from integrating from d to the diagonal formed by d and a.

$$L = \frac{\mu}{\pi} \log \frac{a}{r} \text{ and } M = \frac{\mu}{2\pi} \log \frac{a^2 + d^9}{d^2} .$$

$$L_e = \frac{L + M}{2}$$

$$= \frac{\frac{\mu}{\pi} \log \frac{a}{r} + \frac{\mu}{2\pi} \log \frac{a^2 + d^2}{d^2}}{2}$$

$$= \frac{\mu}{2\pi} \frac{\log \frac{a^2}{r^2} + \log \frac{a^2 + d^2}{d^2}}{2}$$

$$= \frac{\mu}{4\pi} \log \frac{a^2\left(a^2 + d^2\right)}{r^2 d^2}$$

Similarly,

$$L_o = \frac{L+M}{2}$$

$$= \frac{\mu}{4\pi} \log \frac{a^2 d^2}{r^2\left(a^2 + d^2\right)}$$

Now (see The analogy between L, C and R)

$$L_e = \mu f_e .$$

$$\therefore f_e = \frac{\mu}{4\pi} \log \frac{a^2\left(a^2 + d^2\right)}{r^2 d^2} .$$

Also (see The analogy between L, C and R),

$$Z_{0e} = f_e\sqrt{\frac{\mu}{\varepsilon}}\,.$$

Similarly,

$$L_0 = \mu f_0,\ Z_{00} = f_0\sqrt{\frac{\mu}{\varepsilon}}.$$

$$\therefore\ Z_{0e} = \frac{\sqrt{\frac{\mu}{\varepsilon}}}{4\pi}\log\frac{a^2\left(a^2+d^2\right)}{r^2d^2}\,,$$

$$\therefore\ Z_{0o} = \frac{\sqrt{\frac{\mu}{\varepsilon}}}{4\pi}\log\frac{a^2d^2}{r^2\left(a^2+d^2\right)}\,.$$

From Figure 50 and Figure 51, and in the text, we see that the ratio of Maximum Fast Crosstalk to Signal, or FX/Signal, equals

$$\frac{\left(Z_{0e}-Z_{0o}\right)}{\left(Z_{0e}+Z_{0o}\right)}\,.$$

This now comes to equal

$$\frac{\log\frac{a^2\left(a^2+d^2\right)}{r^2d^2} - \log\frac{a^2d^2}{r^2\left(a^2+d^2\right)}}{\log\frac{a^2\left(a^2+d^2\right)}{r^2d^2} + \log\frac{a^2d^2}{r^2\left(a^2+d^2\right)}}$$

$$= \frac{\log\frac{\left(a^2+d^2\right)^2}{d^4}}{\log\frac{a^4}{r^4}}$$

$$= \frac{\log\frac{a^2+d^2}{d^2}}{\log\frac{a^2}{r^2}}$$ [3].

As further justification for the last formula, let us again approach it via inductance.
Looking at Figure 62, we see that the self inductance of pair AB is (the magnetic flux linking between A and B caused by i_a) plus (the flux between A and B caused by i_b).
Each of these results from integrating from r, the radius of a wire, to d, the distance between A and B.
This gives us $\log\frac{a}{r}$.
Now the mutual inductance results from the magnetic flux which these same currents cause to link between P

and Q.

In this case we integrate (twice) between the distance BQ (=d) and the diagonal BP $\left(=\sqrt{a^2+d^2}\right)$.

The result is

$$\log\frac{\sqrt{a^2+d^2}}{d}.$$

As shown previously (see The analogy between L, C and R), Z_0 is analogous to L.
We can see why the formula for Maximum Fast Crosstalk results as calculated above.
It is merely the ratio of fluxes linked across from AB to PQ divided by the flux linked in AB by its own current.

Check on the Validity of Crosstalk Figures.

Reference 15, page749 discusses the use of resistive paper to determine values for Zo (Fig.47), Z_{0e}, Z_{0o}.
Also, values for Graph 48 and Graph 49 can be determined directly by painting conductors onto resistive paper; putting a voltage between A and voltage plane, and measuring the resulting voltage drop between P and voltage plane[4].

Graphs 47 , 48 and 49 were developed using resistive paper with the occasional spot check sending real pulses down real printed circuit boards (ref.15).

Here is an attempt to calculate FX. We try to make the situation in Graph 49 approximate to that in Figure 62 and Table 1(f), which we have calculated.

In Fig.62,

$$\frac{FX}{Signal}=\frac{\log\frac{a^2+d^2}{d^2}}{\log\frac{a^2}{r^2}}.$$

First we note that the major problem is for flux lines to exit from close to the conductor, where there is severe crowding. Therefore we assume that the ruling variable is the perimeter of the conductor. In Fig.49, this is 0.0228". However, the portion (0.0128") which faces air, although in no way inferior for magnetic flux, is less useful for electric flux by a factor of 4.5. Scale that section (arbitrarily) down by x3. Thus the effective (epoxy glass equivalent) perimeter is 0.0100 + 0.0128/3 = 0.0143". Now a circular conductor, as in Fig.62, with that circumference, has radius 0.0023". A reasonable value for distance between A and P is 0.015" to be equivalent to where d in Fig.49 is 0.010". A reasonable value for distance AB (=2h in Figs.44, 49), called a on p24 and in Fig. 62, is 0.015".

$$\frac{FX}{Signal}=\frac{\log\frac{a^2+d^2}{d^2}}{\log\frac{a^2}{r^2}}$$

$$\frac{FX}{Signal}=\frac{\log\frac{150^2+150^2}{150^2}}{\log\frac{150^2}{2.3^2}}$$

$\approx$ ·8%.

This agrees with the central point on the middle curve in Fig.49, where d=0.010", w=0.010" and FX/signal =slightly over 10%.

The important point to remember is that the logarithms of wildly different numbers are very similar. e.g. $\log_{10}$ 10, 100, 100, are a very similar 1, 2, 3. Now in our exercises, only the $\log_e$ (also called l_n) of dimensions appear in calculations. So calculations based on crude approximations lead to remarkably accurate results.

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[1]As the separation between the pairs is reduced, the self inductance rises from L/2 towards L.

[2]because all flux lines caused by current in one pair thread the other pair, so that M=L.

[3]We are allowed to do this strange manoeuver, taking the square root of top and bottom, because log10,000/log100 = log100/log10! However, we tend to lose the indication of the diagonal (hypotenuse BP, Fig.62), in this mathematical trickery, and it all starts to look like a function of distances squared, which it is not. The physical reality is better illustrated by the more awkward formula $\frac{FX}{Signal} = \frac{\log \frac{\sqrt{a^2 + d^2}}{d}}{\log \frac{a}{r}}$

[4]Actually, slice lines A and P horizontally through their middles, and paint B and Q, again sliced through their middles, at the bottom of a strip of resistive paper.

Energy Current.

Oliver Heaviside, who had the advantage of being born later, had a better grasp of electromagnetics than did Faraday or Maxwell, and his view of how a digital signal travels is well worth study[1].

Whereas the conventional approach to the subject today is to concentrate on the electric current in wires, with some additional consideration of voltages between wires, Heaviside concentrates primarily on what he calls 'energy current', this being the electromagnetic field which travels in the dielectric between the wires. In the quotation below, Heaviside's phrase, "We reverse this;" point to the great watershed in the history of electromagnetic theory - between the 'etherials', who with Heaviside believe that the signal is an 'energy current' which travels in the dielectric between the wires, and the 'practical electricians', who like John T. Sprague believe that the signal is an electric current which travels down copper wires, and that if there *is* a 'field' in the space between the wires, this is only the result of what is happening in the conductors.

Heaviside wrote (Ref.22);

"Now in Maxwell's theory there is the potential energy of the displacement produced in the dielectric parts by the electric force, and there is the kinetic or magnetic energy of the magnetic induction due to the magnetic force in all parts of the field, including the conducting parts. They are supposed to be set up by the current in the wire. We reverse this; the current in the wire is set up by the energy transmitted through the medium around it...."

The importance of Heaviside's phrase, "We reverse this;" cannot be overstated for digital designers. It points to the watershed between the 'practical electricians', who have held sway for the last half century, promulgating their theory - which we shall call "Theory N", the Normal Theory: that the cause is electric currents in wires and electromagnetic fields are merely an effect - and the 'ethereals', who believe what we shall call "Theory H": that the travelling field is the cause, and electric currents are merely an effect of these fields.

The situation is of course obscured by the many who claim that it is immaterial which causes which. However, experience shows that it is damaging to ignore causality when trying to assemble reliable digital systems.

Before continuing with Theory H, we shall quote one early Theory N man, a 'practical electrician' named John T. Sprague. In his book, ref.23, he ridicules Theory H;

"A new doctrine is becoming fashionable of late years, devised chefly in order to bring the now important phenomena of alternating currents under the mathematical system. It is purely imaginary ... based on Clerk-Maxwell's electromagnetic theory of light, itself correctly described by a favourable reviewer as 'a daring stroke of scientific speculation,' alleged to be proved by the very little understood experiments of Hertz, and supported by a host of assumptions and assertions for which no kind of evidence is offered; but its advocates call it the 'orthodix' theory.

"This theory separates the two factors of electricity ..., and declares that the 'current', the material action, is carried by the 'so-called conductor' (which according to Dr Lodge contains nothing, not even an impulse, and according to Mr. O. Heaviside is to be regarded as an obstructor), but the energy leaves the 'source' (battery or dynamo) 'radiant in exactly the same sense as light is radiant', according to Professor Sylvanus P. Thompson, and is carried in space by the ether: that it 'swirls' round (cause for such swirling no one exaplains) and finds its way to the conductor in which it then produces the current which is apparently merely an agency for clearing the ether of energy which tends to 'choke' it, while the conductor serves no other purpose than that of a 'waste pipe' to get rid of this energy ...

"This much, however, is certain; that if the 'ether' or medium, or di-electrics carry the energy, the practical electrician must not imagine he can get nature to do his work for him; the ether, &c., play no part whatsoever in the calculations he has to make; whether copper wire is a conductor or a waste pipe, that is what he has to provide in quantity and quality to do the work; if gutta percha, &c., really carry the energy, he need not trouble about providing *for that purpose*; he must see to it that he provides it according to the belief that it prevents loss of current. In other words, let theoretical mathematicians devise what new theories they please, the practical electrician must work upon the old theory that the condctor does his work and the insulation prevents its being wasted. Ohm's law (based on the old theory) is still his safe guide.

"For this reason I would urge all practical electricians, and all students who desire to gain a clear conception of the actual operation of electricity, to dismiss from their minds the new unproved hypotheses about the ether and the abstract theory of conduction, and to completely master the old, the practical, and common sense theory which links matter and energy together..."

Sprague accurately described Theory N, which has been used in practice by virtually every digital designer, with disastrous results. They must now turn to Theory H to get them out of their difficulties.

In his book (ref.24), J. A. Fleming argued for Theory H;

"It is important that the student should bear in mind that, although we are accustomed to speak of the current as *flowing in the wire* in one direction or the other, this is a mere form of words. What we call *the current* in the wire is, to a very large extent, a process going on in the space or material outside the wire. Just as we familiarly speak of the sun rising and setting, when the effect is really due to the rotation of the earth, so the ordinary language we use in speaking about electric currents flowing in conductors retains the form impressed upon it by older and erroneous assumptions as to their nature."

The reader will have surmised by now that "energy current", the primary signal which travels down the dielectric from one logic gate to the next, has an amplitude equal to the Poynting vestor, E x H.

We shall end this qualitative discussion with some of the more important quotations from Heaviside, the man who a century ago brilliantly used the concept of energy current to solve telegraph problems which closely parallel present-day problems in high speed digital logic.

Heaviside wrote (ref.22);

"It becomes important to find the paths along which the energy is being transmitted. First define the energy-current at a point to be the amount of energy transferred in unit time across unit area perpendicular to the direction of transmission ... This is true universally, irrespective of the nature of the medium as to conductivity, capacity and permeability ... and is true in transient as well as in steady states. A line of energy-current is perpendicular to the electric and the magnetic force, and is a line of pressure, We here give a few general notions.

"Return to our wire from London to Edinburgh with a steady current from the battery in London The energy is poured out of the battery *sideways* into the dielectric at a steady rate ... Most of the energy is transmitted parallel to the wire nearly ... But some of the outer tubes go out into space to an immense distance ... If there is an instrument in the circuit at Edinburgh, it is worked by energy that has travelled wholly through the dielectric, then finding its way into the instrument, ... where it enters ... and is there dissipated ...

"In a circular circuit, with the battery at one end of a diameter, its other end is the neutral point; the lines of energy-current are distributed symmetrically with respect to the diameter.

"On closing the battery circuit (i.e. switching the logic output) there is an immediate rush of energy into the dielectric ..."

The Theories

A number of different dualisms obtain within or in the vicinity of electromagnetic theory as it is developing. the student needs to be warned against thinking that only one dualism is involved, and that he is merely seeing different expressions of the same dualism. The mutually distinct dualisms include:

wave-particle dualism

Theory N - Theory H (ref.18a)

The Rolling Wave - The Heaviside Signal (ref.18b p51)

It will be seen later that one of these is in fact a three-way split between Theory N, Theory H and Theory C.

Historical development.

The transition from classical, wireless-based electromagnetic theory, loosely equivalent to Theory N, to one of the preferred theoretical positions for the digital electronic designer, Theory H or Theory C, is via a complex development shown in Figure 63.

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[1] Chapter previously published in Ref.3(a) p65.

The capacitor

In the early 1960's I pioneered the inter-connection of high speed (1nsec) logic gates at Motorola, Phoenix, Arixona (ref.25). One of the problems to be solved was the nature of the voltage decoupling at a point given by two parallel voltage planes. I asked Bill Herndon about the problem, and he gave me the answer: "It's a transmission line".[1] Bill learnt this from Stopper, whom I never met, who later worked for Burroughs (UNISYS) Corp. in Detroit.

The fact that parallel voltage planes, when entered at a point, present a resistive, not a reactive, impedance, was for me an important breakthrough. (It meant that as logic speeds increased, there would be no limitation presented by the problem of supplying +5v.) The reader should be able to grasp the reason why voltage plane decoupling is resistive by studying Figure 64, which shows the effect of a segment only of two planes as they are seen from a point.

During the next ten years, with the help of Dr. D. S. Walton, I gradually came to appreciate that, since a conventional capacitor was made up of two parallel voltage planes it also had a resistive, not a reactive (i.e. capacitive or inductive) source impedance when used to decouple the +5v supply to logic. Since the source impedance (= transmission line characteristic impedance) is well below one ohm, the transient current demand of logic gates approaching infinite speed can still be successfully satisfied with +5v from a standard capacitor of any type[2].

The capacitor is an energy store, and when energy is injected, it enters the capacitor *sideways* at the point where the two leads are joined to the capacitor. Nothing ever traverses a capacitor from one plate to the other[3]. This is clearly understood in the case of a transmission line. By definition, when a TEM wave travels down a transmission line, Figure 5, nothing travels sideways across the transmission line, or we would not have a transverse electromagnetic wave.

Comparison of the transmission line model with the lumped model of a capacitor in an RC circuit.

Consider a transmission line as shown in Figure 65 with

characteristic impedance Zo terminating in an open circuit. We will assume that R>>Zo.

When the switches are closed (at time t=0) a step of voltage $V\frac{Z_0}{R+Z_0}$ is propagated down the line. This

reflects from the open circuit at the right hand end to give a total voltage of $2V\frac{Z_0}{R+Z_0}$. Reflection from the left

hand end makes a further contribution of $V\frac{Z_0}{R+Z_0}\,\frac{R-Z_0}{R+Z_0}$ and so on. In general, after n two-way

passes the voltage is V_n and;

$$V_{n+1} = V_n + 2V\frac{Z_0}{R+Z_0}\left[\frac{R-Z_0}{R+Z_0}\right]^n \quad (1)$$

In order to avoid a rather difficult integration it is possible to sum the series to n terms using the formula

$$\sum V = a\frac{1-v^n}{1-v} \quad (2)$$

where a is the first term of a geometrical progression and v the ratio between terms. (This formula is easily verified by induction.) Substituting in (2) the parameters for (1),

$$a = 2V\frac{Z_0}{R + Z_0} \quad (3)$$

$$V = \frac{R - Z_0}{R + Z_0} \quad (4)$$

We obtain,

$$V_n = 2V \frac{\dfrac{Z_0}{R + Z_0}\left[1 - \left\{\dfrac{R - Z_0}{R + Z_0}\right\}^n\right]}{1 - \dfrac{R - Z_0}{R + Z_0}} \quad (5)$$

$$= V\left[1 - \left\{\frac{R - Z_0}{R + Z_0}\right\}^n\right] \quad (6)$$

This is a correct description of what is happening as a capacitor charges. We can now go on to show that it is approximated by an exponential. We have

$$V_n = V\left[1 - \left\{\frac{R - Z_0}{R + Z_0}\right\}^n\right] \quad (7)$$

Consider the term,

$$T = \left[\frac{R - Z_0}{R + Z_0}\right]^n .$$

$$= \left[\frac{1 - \dfrac{Z_0}{R}}{1 + \dfrac{Z_0}{R}}\right]^n .$$

If Zo/R<<1 this term is asymptotically equal to

$$T = \left[1 - \frac{2Z_0}{R}\right]^n .$$

Now define

$$k = 2Z_0 \frac{n}{R}.$$

Substitution gives

$$T = \left(1 - \frac{k}{n}\right)^n.$$

By definition, as $n \to \infty$ we have,

$$T = e^{-k} = e^{-\frac{2Z_0 n}{R}}.$$

and therefore:

$$V_n = V\left(1 - e^{-\frac{2Z_0 n}{R}}\right).$$

Now, after time t, $n = \frac{C}{2l}$, where C = velocity of propagation.

Thus,

$$V(t) = V\left[1 - e^{-\frac{Ct}{l}\frac{Z_0}{R}}\right].$$

For any transmission line it can be shown (p19) that

$$Z_0 = f\sqrt{\frac{\mu}{\varepsilon}},\ C = \frac{1}{\sqrt{\mu\varepsilon}},\ c = \frac{\varepsilon}{f}$$

where c= capacitance per unit length and f is a geometrical factor in each case. The "total capacitance" of length l

$$= lc = C.$$

Hence,

$$\frac{CZ_0}{lR} = \frac{1}{RC}$$

and therefore

$$V(t) = V\left[1 - e^{-\frac{t}{RC}}\right]$$

which is the standard result. This model does not require use of the concept of charge. A graphical comparison of the results is shown in Figure 66. [4]

Ref 25: Catt I., et al., A High Speed Integrated Circuit Scratchpad Memory, Fall Joint Computer Conference, Nov. 1966.

[1]ref.15, p40.

[2]Ref.3b, p216, refutes the fashionable nonsense about "RF capacitors".

[3]Similarly, the battery, p13, note 24, and the electrolyte.

[4]Calculations were by my co-author Dr. D.S. Walton. First published in Wireless World, dec78, p51.

The diode as an energy-controlled, not a charge-controlled device.

The traditional theory of operation of the diode is, for me, one of the many casualities of advances in electromagnetic theory during the last 25 years[1].

Whilst at Motorola, Phoenix, in 1964, work on the problem of how to interconnect high-speed (one nanosecond) logic gates led me to the same general conclusion as had been reached (unknown by me until 1972) by Oliver Heaviside a century before when he tackled the problem of how to improve undersea telegraphy from Newcastle to Denmark[2].

"... [The electric and magnetic fields] are supposed to be set up by the current in the wire. We reverse this; the current in the wire is set up by the energy current through the medium around it. The sum of the electric and magnetic energies is the energy....

".... A line of energy-current is perpendicular to the electric and magnetic force...."

Our conclusion was that what he called "energy current" travelling down between the two conductors[3] guided by them as a train is guided by two rails, was the important feature of signalling, and not the electric charge and electric current in or on the wires. Twenty years later my view hardened when I came across the Catt Anomaly.

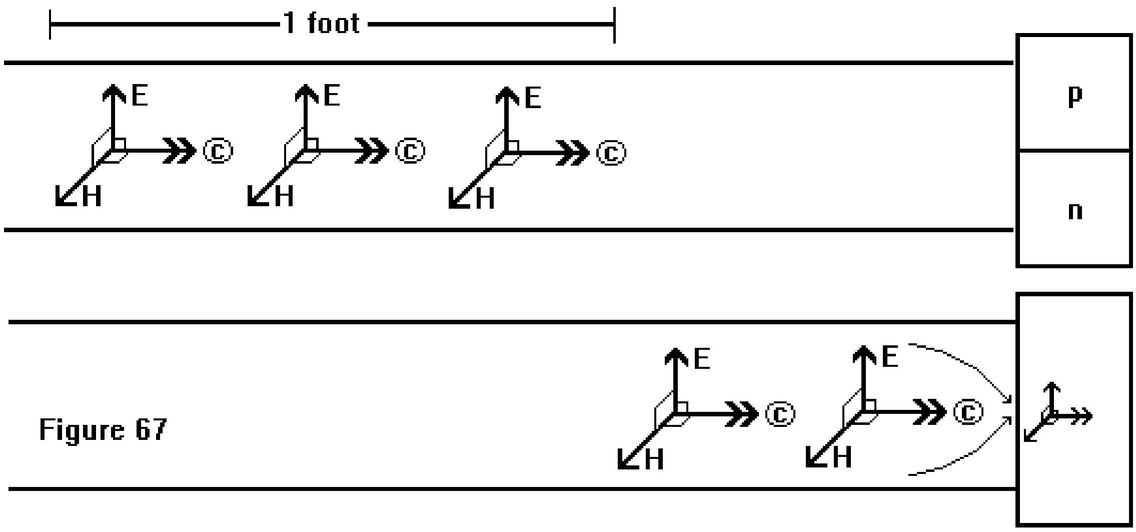

Figure 67

Let us deliver a 1ns-wide pulse down a long transmission line terminated by a diode (Fig.67). When the pulse reaches the diode, *it does not carry any charge with it*. Catt's Anomaly shows that charge could not have travelled fast enough to keep up with the pulse, which travels at the speed of light. If we are agreed that the diode will respond (for instance 'start to conduct') after a delay which is small (say 100ps) compared with the time delay down the transmission line delivering the pulse, then it must be responding to the *energy current*, that is, the TEM wave or pulse approaching it in between the two conductors. This TEM pulse enters directly into the side of the crucial interface or surface between the p-region and the n-region which together make up the diode.

Note the phrase on page 30 col.2; "Nothing ever traverses a capacitor from one plate to the other". Applied to the diode, this seems to say that nothing travels across the junction from the p-region to the n-region, or vice versa. The only travel is along the surface between the two regions, in a direction at right angles to the generally supposed direction of movement.

When the leading edge of the pulse reaches the near edge of the diode, it finds a change in characteristic impedance. As a result, most of it is reflected, but a small portion continues forward to the right, down the very narrow transmission line made by the surface between the p and n regions. It is possible that the effective dielectric constant ε is large so that the velocity of propagation, $\frac{1}{\sqrt{\mu\varepsilon}}$, from left to right along the p-n interface is very slow. At the speed of light in a vacuum, the round trip across the p-n interface of a diode a tenth of an inch wide would be 20 picoseconds, but since the effective ε will be bigger than for a vacuum, the delay will be greater.

When the step reaches the right-hand edge of the diode, it sees an open circuit and reflects back toward the left, so that the total voltage across the junction doubles. When it gets back to the front (left-hand) end, it reflects toward the right again (except for the very small portion which escapes across the Zo mismatch back into the transmission line leading away to the left). By this mechanism of zig-zag repeated reflections across[4] the diode, the amount of energy (current) in the p-n surface increases in a series of diminishing steps which approximates to an exponential (Fig.66). When the energy density builds up beyond some critical level (0.7v), there is a 'snap', and the later advancing energy current sees a short circuit, and reflects with inversion[5].

Since no charge has been introduced into the p-n interface, it is totally inappropriate to explain the mechanism of the diode in terms of extra electrons. The explanation must be novel, in terms of the amount of electromagnetic energy present; that a level in excess of some critical value (0.7v) causes the TEM wave travelling down the p-n interface to see a change in what is ahead of it, from open circuit to short circuit. That is, beyond that critical amplitude the p-n interface cannot accept more energy and rejects it.

This developing analysis of the behaviour of a diode is totally at odds with the traditional view, based on electrons, holes, energy barriers across the p-n interface that charges are trying to climb up. Why does this earlier theory succeed in correlating *at all* with experimental results?

"... if in conversation you insisted that your elder daughter was *identical* to your younger daughter, whereas in fact their "equality" only related to their parentage, every conclusion that followed this absurd assertion would not necessarily be absurd. For instance, if you knew the address of one daughter you might therefore know the address of the other. In the same way, it is possible for 'valid' results to come from absurd postulates (like the absurd postulate that a diode is full of particles called electrons buzzing around trying to climb hills [in the wrong direction at the wrong speed]).

"... the two non-identical daughters might have the same address. It is these 'echoes of truth' which masquerade as scientific truth today" (ref. ll vol 1, p15).

False theories, like the theory that the diode is a device controlled by charge, exist in the real world, and so are influenced, or somewhat directed, by the imperatives of the real world in which they find themselves, at least when it comes to the moment of truth: the checking of theory against experimental result.

The Catt Question. (Was Catt's Anomaly.)

Traditionally, when a TEM step (i.e. a logic transition from low to high) travels through a vacuum from left to right (Fig.1), guided by two conductors (the signal line and the 0v line), there are four factors which make up the wave: (1) electric current in the conductors, (2) magnetic field, or flux, surrounding the conductors, (3) electric charge on the surface of the conductors, (4) electric field, or flux, in the vacuum terminating on the charge.

The key to grasping the anomaly is to concentrate on the electric charge on the bottom conductor. During the next 1 nanosecond, the step advances one foot to the right. During this time, extra negative charge appears on the surface of the bottom conductor in the next one foot length, to terminate the lines (tubes) of flux which now exist between the top (signal) conductor and the bottom conductor.

Where does this new charge come from? Not from the upper conductor, because by definition, displacement current is not the flow of real charge. Not from somewhere to the left, because such charge would have to travel at the speed of light in a vacuum. (This last sentence is what those "disciplined in the art" cannot grasp, although paradoxicallyt it is obvious to the untutored mind.) A central feature of conventional theory is that the drift velocity of electric current is slower than the speed of light.

For further information on the Catt Anomaly, see letters in the following issues of Wireless World; aug81, aug82,oct82,dec82, jan83.

Heaviside and the Catt Anomaly.

Oliver Heaviside did his work on Energy Current too early to discern the Catt Anomaly. The idea that electric current comprised electrons was still only an "ingenious .... theory [by] J. J. Thomson" in the 1905 Harmsworth Encyclopaedia, p2184. So the firm conviction that the electrons which comprised electric current had mass came too late for Heaviside.

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[1] This section was first published in Electronics and Wireless World, September 1987, p903.

[2] ref.5c.

[3] i.e. the Poynting Vector.

[4] These insights will meet the same indifference as was discussed in Footnote 24, p13.

[5] I agree with L. Turin that this is simplistic, since the forward voltage drop of a diode is not sharp, and follows a law which includes electric current and temperature. The purpose of this section is to take the first step away from the conventional theory, which is obviously balderdash. Since it was first published in 1987 it has excited no comment, not even a riposte.

Cumulative index

This is a cumulative index covering past books and articles, with the following abbreviations;

Two volumes DIGITAL ELECTRONIC DESIGN (D),

the Macmillan book DIGITAL HARDWARE DESIGN (M),

two books ELECTROMAGNETIC THEORY (E),

and some Wireless World and Electronics and Wireless World articles (WW), later published in the book

DEATH OF ELECTRIC CURRENT (DEC).

Glossary of Terms

Buried conductor. See "Stripline". p17.

Catt Anomaly. First described in Wireless World, aug81. When a voltage step travels down a two wire transmission line, more and more negative charge must appear on the lower line to terminate the electric flux. This has to travel from the left at the speed of light, but in that case the electrons have infinite mass. p31. [My 1996 book *The Catt Anomaly* pub. Westfields, is on my website www.electromagnetism.demon.co.uk/]

Characteristic impedance. If the front end of a long coaxial cable behaves like a 50w resistor, then we say that the line has a characteristic impedance of 50w. It would be more accurate if we called it "Characteristic resistance", but we don't. p24.

Crosstalk. When a signal travels down one line with ground as return path, it causes unwanted electrical noise on an adjacent signal line. Originally (1960) thought to be due to stray capacitance between the signal lines in the high voltage and low current signals used in valve circuits, the advent of lower voltages and heavier electric currents in transistor circuits moved some of the attention towards stray mutual inductance, creating a hybrid theory. Although these false rationalisations have some use when only a crude feel for the problem is needed, they must now give way to the concept of the two propagation modes, EM and OM.

DX. Differential Crosstalk. Name devised in my 1967 paper (ref.15). Differential crosstalk arises in surface lines because the Even Mode and the Odd Mode signals have different propagation velocities. The faster, negative OM arrives at the far end of the passive line before the (partly cancelling) EM signal. DX reaches a maximum of about 50% of the original signal, but only in very long lines. Fig. 49, p18 gives the velocity difference which causes DX. Fig. 50, p19.

EM. Even Mode. p16 One of the two types of signal which can travel along a symmetrical four wire system.

Energy current. p14, p28 The counterpoint to electric current. A phrase used only twice by Heaviside late last century as the foundation of his Theory H, in which the cause is energy current, or the Poynting Vector, guided along between the conductors at the speed of light, and causing the electric current and charge in the conductors, which he called "obstructors". Energy current was never mentioned again until Catt discovered it. Previous Heaviside savants Josephs, Gossick, Mercer, all of whom I have met, overlooked it. The Poynting Vector is an early version of it, and it later became the TEM Wave.

FX. Fast Crosstalk. Name devised in my 1967 paper (ref.15). A flat topped pules, the difference between the Even Mode and the Odd Mode signal which is seen on the passive line. Fig.50, p19.

Microstrip. See "Surface conductor". p18.

OM. Odd Mode. p16 One of the two types of signal which can travel along a symmetrical four wire system.

Surface conductor. Microstrip. A printed wire on the outside surface of a printed circuit board. p18.

Stripline. A printed wire sandwiched between two voltage planes in a printed circuit board. p17.

SX Slow Crosstalk. Name devised in my 1967 paper (ref.15). The degenerate case of FX, when propagation time down the passive line and back is less than the signal rise time. SX has the triangular (noise spike) shape that we are all familiar with in slower logic.

TEM Wave. Transverse Electromagnetic Wave. Fig5, p2 This neglected concept is the central feature of Catt's theory of electromagnetism. Conventionally, the TEM wave has a B component in the x direction, an E component in the y direction, and travels forward in the z direction at the speed of light, 300,000 km/s (in vacuo).

Under Theory C, the TEM wave is the only physically possible expression of electric field and of magnetic field. The two fields are indissolubly linked in the ratio 377w (in vacuo). Further, such a field cannot be stationary. It can only travel at the speed of light. Stationary electric and magnetic fields do not exist. Fields travelling at other than the speed of light do not exist.

Theory C. First disclosed In Wireless World, dec80. The third in the sequence (p29) of fundamental theories of electromagnetism. C stands for Catt. Catt realised that when Theory H reversed the causality between electric current and field, it led to the disappearance of the need for current and charge. This excision resolves the Catt Anomaly (p31). p12

Theory H. The second in the series of theories. H stands for Heaviside. "We reverse this; the current in the wire is set up by the energy transmitted through the medium around it ..."

Theory N. The conventional theory of electromagnetism which has ruled for a century since the suppression of Oliver Heaviside and his supporters. A battery yearns to send electric current down wires. If it succeeds, this results in electric field, or flux, between the wires, and magnetic field, or flux, surrounding the current in the wires.

Transverse Electromagnetic Wave. See TEM Wave.

Index

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b) ref 2b, p. 73, eqn. (6).

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a) Ref.3a, p. 65; Ref.3b, pp.119, 327, also p319

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Electromagnetism 1

by Ivor Catt

Westfields Press 1994

"The main body of the text is devoted to transmssion lines ....

There are numerous examples of sloppy argument in the text. .... The flaws in these arguments are easy to see. ....

The author sees an anomaly in the conventional view of the transmission line. This he calls the 'Catt anomaly' and it is the starting point of his proposals for an improved theory.

The 'Catt anomaly': When a TEM wave travels along a transmission line, there must, according to conventional theory, be charge distributions on the surfaces of the conductors behind the wavefront. For a vacuum dielectric the speed of the wavefront is the speed of light so that, according to Catt, the charges on the conductors must travel at the speed of light, which is impossible. This is the 'Catt anomaly'. Since the wavefront does travel at the speed of light, so do the charges, which then have infinite mass. It follows that there cannot be charges on the conductor surfaces and conventional theory must be wrong.

The flaw here is the assumption that the charges move with the wave. whereas in reality they simply come to the surface as the wave passes, and when it has gone they recede into the conductor. No individual charge moves with the velocity of the wave. The charges come to the surface to help the wave go by and then pass the task to other charges further along the line which are already there and waiting. This is the mechanism of guidance and containement. There is no anomaly.

But Catt goes on. Having removed charges from the surfaces of his conductors, he can no longer apply Gauss's law and the displacement current in the wave has to go somewhere. Catt's solution is typically ingenious: the current must continue as displacement current in conductors, which are actually dielectrics with a very high permittivity; there is no conduction current in conductors - ever! Catt's Ockham's Razor has been wielded to remove conduction current as well as electric charge from electromagnetic theory. There is of course the small problem of a value for the permittivity of copper. Catt is equal to the challenge .... the permittivity of copper must be extremely large. ....

.... It is significant that, having introduced his new theory and abolished charge and current ...., he then proceeds to use these concepts quite unashamedly in the rest of the book. ....

There are many other items in this book which give cause for concern, for example the false statement that 'The TEM wave has virtually disappeared from today's electromagnetic theory'.

Catt's belief in his own work is clearly sincere, but this reviewer, after lengthy and careful consideration, can find virtually nothing of value in this book.

B. LAGO

The penultimate paragraph above echoes Lago's earlier letter in Wireless World (July79) where he attacked my articles "Displacement Current" that appeared in Wireless World, Dec78 and March79:-

> " .... the articles are wrong in almost every detail and it is vital that this should be clearly demonstrated before undue damage is done. ....
>
> May I suggest that your readers will be well advised to approach the "further reading" with caution."

Lago has surfaced just twice with his large spanner. I know nothing of him except that he is at Keele University.

-Ivor Catt feb01

Also see:

A difficulty in electromagnetic theory,
The Lynch / Catt IEE 10july98 paper given at the IEE Group S7 conference.

Back to Electromagnetism 1 - Index page